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DESIGN AND EVALUTION OF A SONOBUOY
RANGING SYSTEM

John Richard Ellis

United States
Naval Postgraduate School

THESIS

DESIGN AND EVALUATION OF
A SONOBUOY RANGING SYSTEM

by

John Richard Ellis

June 1970

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Design and Evaluation of
A Sonobuoy Ranging System

by

John Richard Ellis
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1962

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

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, CALIF. 93940

ABSTRACT

Airborne anti-submarine warfare operations require a means of precise tactical navigation relative to an air-dropped sonobuoy pattern. Advantages and disadvantages of navigational techniques which could be used to solve this problem are discussed. An analysis is made of a previously proposed method to solve this problem by sonobuoy ranging concepts. The design of a prototype sonobuoy ranging system is described, and a preliminary evaluation is made of the accuracy of the prototype system.

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ACKNOWLEDGEMENT

Mr. Robert C. Smith and Mr. James P. Bly, of the Naval Postgraduate School Research Staff, were of invaluable assistance in the construction of the prototype sonobuoy ranging system described in this paper. A great debt is owed to them for their timely suggestions and ideas which assisted in solving some of the engineering problems that were encountered. Their technical knowledge, based on a broad background of experience, greatly enhanced the quality of the final prototype, and working with them was an educational and rewarding experience.

I. INTRODUCTION

One of the major problems encountered in present airborne anti-submarine warfare (ASW) systems is the inability to achieve precise tactical navigation with reference to an air-dropped sonobuoy pattern. Before considering a solution to this problem, one must have a good understanding of tactical navigation techniques used in ASW operations. Having had a great deal of personal experience in airborne ASW operations, the author will draw on that experience to describe the problem.

A. A DESCRIPTION OF THE ASW TACTICAL NAVIGATION PROBLEM

The normal situation is one where the aircraft uses a field of air-dropped sonobuoys as sensors to transmit information to the aircraft. The aircraft has electronic equipment on board which processes this information and determines the position of any detected submarine relative to the sonobuoys in the pattern. Although the determined position of the submarine relative to the sonobuoys is usually quite accurate, the aircraft may still be unable to locate the sub for an accurate attack. This is usually due to the fact that the aircraft cannot determine its own position relative to the sonobuoys as accurately as the submarine's position relative to the sonobuoys. Therefore, the resulting accuracy of the position plotted for the submarine on the tactical plot in the aircraft is limited by the accuracy of the aircraft's knowledge of its own position relative to the sonobuoys.

Lack of knowledge of precise relative positions also causes problems during the localization phase of the ASW problem, long before any attack is contemplated. After a submarine is initially detected

(usually at a long range from the aircraft), present ASW systems require that the aircraft continuously refine the position of the detected submarine into a smaller and smaller area. Because the accuracy of present tactical navigation methods tends to decrease with elapsed time since the last visual location of the sonobuoys, the aircraft must continuously update the position of the sonobuoys to obtain positioning information accurate enough to permit an attack on the submarine. This greatly limits the tactical mobility of the aircraft.

If a tactical navigation system could be developed which would permit the aircraft to manuever freely after the initial drop of the sonobuoys, and which would also retain the accuracy required for a successful attack after a long time delay <u>without</u> repositioning of the sonobuoys, the tactical mobility of the aircraft and the speed with which the localization phase could be prosecuted could be greatly increased. It might even be possible to proceed to an accurate attack position from long ranges immediately after detection without further localization. The advantage of being able to make an immediate attack after detection should be immediately obvious, especially when considering tactics against modern, high-speed nuclear submarines.

To solve this problem of obtaining precise tactical navigation, what is needed is some means of determining the precise location of the aircraft relative to the sonobuoys in the dropped pattern. Such a system should be passive from the aircraft's point of view to retain the advantage of surprise. Transmissions by the aircraft could give his presence away to the enemy, and should not be required. Such a system should also not limit the tactical mobility of the aircraft.

The system should be accurate for time delays as long as the life time of the buoy or the length of the aircraft mission, whichever is shorter. The maximum range at which the system would normally be used would be within 70 nautical miles of the sonobuoy. Although desirable, such a system would not necessarily have to provide accurate geographic positioning. This could be accomplished by locking the relative tactical plot created by such a system to a geographic grid by having the aircraft take a geographic fix with its global navigation system while at some known position on the tactical plot.

Size, weight, power requirements, and cost are all factors which must be closely considered when contemplating any system which may require modification of the present sonobuoy design. This is emphasized by a number of considerations which are discussed in Chapter III where design modifications to the sonobuoy are considered.

One of the first ideas that comes to mind for solving the tactical navigation problem is a transponder/direction-finding unit which could accurately determine the relative position of aircraft to sonobuoy. However, a transponder would require interrogation by the aircraft, thus making it susceptible to being detected. In addition, radio direction finders are inherently inaccurate unless elaborate antenna systems are used, which is not practical in an aircraft due to size limitations. Any transponder unit of either the radar or radio beacon type would require the addition of a receiver to existing sonobuoy circuitry, and also an additional transmitter if the transponder signal could not be transmitted by the present sonobuoy transmitter. Weight and power limitations due to the additional circuitry required in the sonobuoy would probably preclude using the transponder

idea regardless of other considerations. A transponder could require an additional transmitter and receiver aboard the aircraft as well, thus increasing the cost and complexity of the system.

Radar alone does not appear to be a possible solution due to the low freeboard of the sonobuoy in the water and lack of good radar reflectivity. A radar reflector could overcome this shortcoming, but would be difficult to construct into the small sonobuoy package.

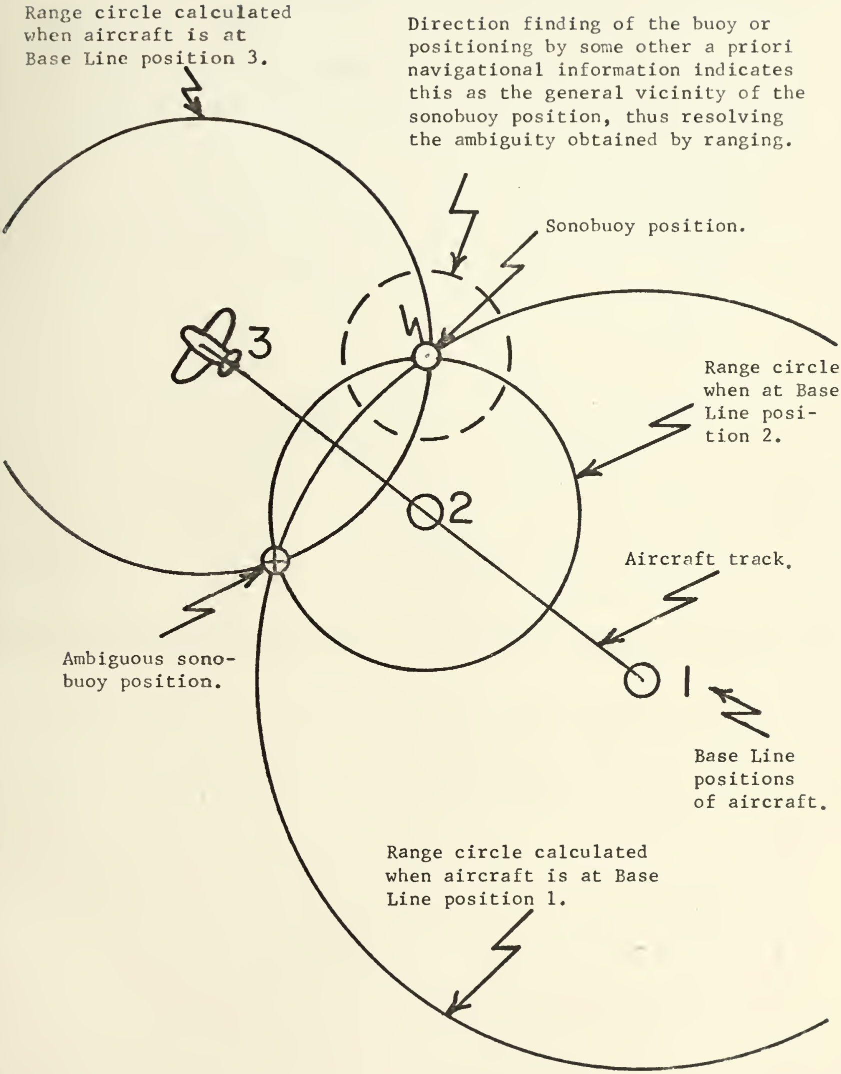
B. A DESCRIPTION OF THE RANGING CONCEPT AS A POSSIBLE SOLUTION

Since the sonobuoy has a transmitter already built in, it appears that a possible solution would be to use it to transmit a signal to the aircraft which could be used to determine range to the sonobuoy. The transmission of this ranging signal by only the sonobuoys would maintain the passive role of the aircraft since no aircraft transmission would be necessary. If the ranging signal could be carried by existing sonobuoy transmitters, no new receivers or transmitters would be needed in the sonobuoy or the aircraft. Only a modification to the detector section of existing aircraft sonobuoy receivers would be required to separate the ranging signal from the sensor signals being received concurrently.

After the range from aircraft to sonobuoy is accurately determined, there are a number of ways in which the range could be used to solve the navigation problem and to maintain an accurate tactical plot. One way has been discussed in detail by Cooley [Ref. 1]. Other ways are also presently being investigated in thesis work yet to be published at this school.

In general, if the onboard navigation system can maintain a plot of the track of the aircraft as a baseline, then measurements of the sonobuoy's range from the aircraft made at various points along the base line will intersect at two locations as shown in Figure 1. Only one of the two locations would be the actual position of the sonobuoy relative to the aircraft track. The other is an ambiguous position. The ambiguity could be resolved by various methods. One method would be to use direction finding information of the sonobuoy's position to point out the actual position. Another method would be to rely on a priori navigational information obtained from some other navigation system in the aircraft which would indicate the general vicinity of the sonobuoy's relative position accurately enough to resolve the ambiguity. If ranging information for ranges to a number of the sonobuoys in the pattern could be measured continuously, a continuous tactical plot could be maintained by the aircraft navigation system so that the aircraft's position relative to the sonobuoy pattern (and hence its position relative to the submarine) would be accurately known at all times.

The advantages of such a ranging system as described above appear to fulfill all of the desirable qualities for a tactical navigation system as outlined earlier. This thesis is concerned only with the problem of obtaining an accurate measurement of slant range from the aircraft to a reference sonobuoy, and not with the solution of the navigation problem using this generated ranging information. The design and evaluation of a prototype ranging system are discussed on a conceptual and functional basis in later chapters. More detailed and technical descriptions of the components making up the prototype



SONOBUOY RANGING FOR TACTICAL NAVIGATION

FIGURE 1

system are given in the appendices. However, the first necessary task in this project was to define a technique for transmitting a signal to the aircraft by which the ranging concept discussed above could be accomplished. This will be discussed thoroughly in the next chapter.

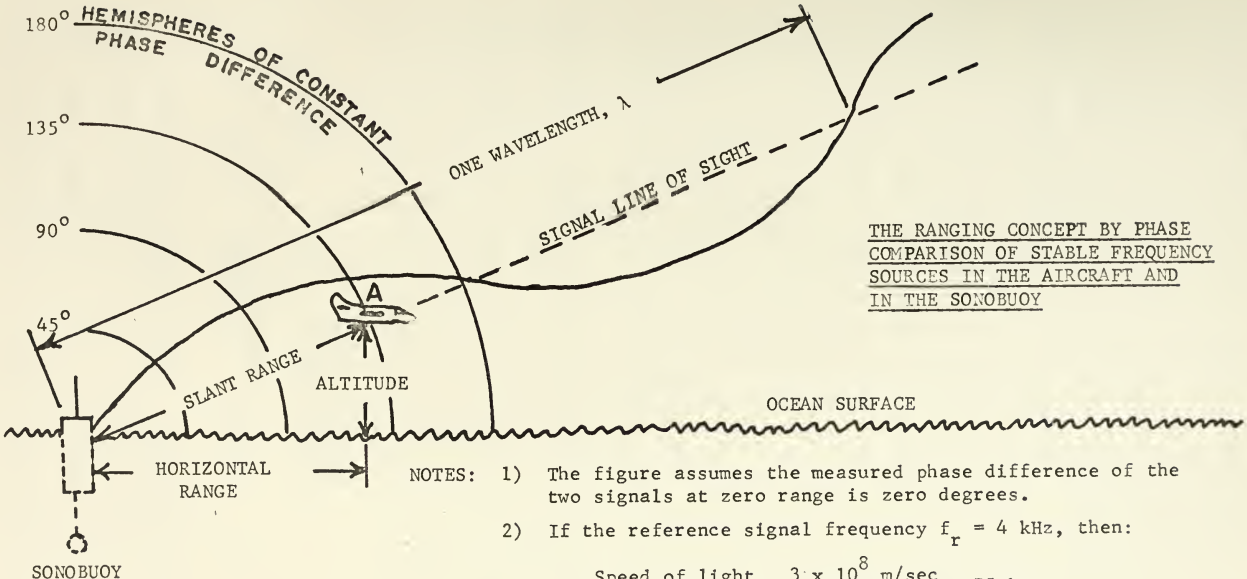
II. A TECHNIQUE TO IMPLEMENT THE RANGING CONCEPT

A technique which could determine range to a transmitter for navigational purposes has been described by Dean [Ref. 2] and by Thomas [Ref. 3] for use in a short-range, precise navigational system. Grant proposed this same phase comparison technique for use in the sonobuoy ranging problem being considered in this thesis and made a preliminary investigation of its feasibility. [Ref. 4]

A. PHASE-COMPARING STABLE FREQUENCY STANDARDS

The basic technique involved is to create the ranging signal in the sonobuoy by means of a frequency-stable signal source and transmit the signal to the aircraft where it is phase compared to another frequency-stable source of the same frequency. By comparing this instantaneous phase difference measurement at an unknown range with a previous phase difference measurement determined at a known range, the accumulated phase difference between the two measurements indicates how much the slant range has changed since the time instant when the range was known. The best way to visualize this is by an example with a diagram of the situation.

Figure 2 shows a diagram of the geometry involved between the aircraft and the sonobuoy. It is assumed, for ease of illustration, that the phase comparison of the sonobuoy ranging signal and the aircraft reference signal was measured to be zero degrees when the aircraft was at zero range (measurement obtained at time sonobuoy was dropped and neglecting the aircraft's altitude at zero range). If the two signals are perfectly stable and equal in frequency, the phase



THE RANGING CONCEPT BY PHASE COMPARISON OF STABLE FREQUENCY SOURCES IN THE AIRCRAFT AND IN THE SONOBUOY

NOTES:

1) The figure assumes the measured phase difference of the two signals at zero range is zero degrees.

2) If the reference signal frequency f_r = 4 kHz, then:

$$\lambda = \frac{\text{Speed of light}}{f_r} = \frac{3 \times 10^8 \text{ m/sec}}{4000 \text{ Hz}} = 75 \text{ km}$$

3) The instantaneous phase difference measured by the aircraft at point A is 135°. Therefore, the slant range is given by:

$$R_s = \frac{135^\circ}{360^\circ} \cdot \lambda = 28.1 \text{ km}$$

THE RANGING CONCEPT

FIGURE 2

difference between the two signals will increase in direct proportion to the slant range to the sonobuoy as the aircraft tracks away from the sonobuoy. This accumulating phase difference will be due to the increasing transit time required for the transmitted signal to travel the increasing distance to the aircraft.

It is seen in Figure 2 that the aircraft transits through hemispheres of constant phase difference as it moves away from the zero phase/zero range reference position measured on top of the sonobuoy. If the transmitted signal is considered as an electro-magnetic wave of wavelength λ, the signal can be visualized as a wave pattern along the line of sight to the aircraft as shown in Figure 2. The phase of the ranging signal, when compared to the reference signal on the aircraft, is shown in this example to be measured as 135 degrees different than at the reference position initially obtained (zero phase/zero range in this case). Since the phase of a signal can be related to a range by means of the wavelength of the signal, the change in range can be obtained from the measured phase difference of 135 degrees. For this example, where a 4-kHz reference signal is being used, this could be interpreted as an exact slant range value, R, as follows:

$$R = \frac{\Delta\phi}{360^{\circ}} \cdot \lambda = \frac{135^{\circ}}{360^{\circ}} \cdot \frac{\text{Speed of light}}{\text{Signal frequency}}$$

$$\therefore R = \frac{135^{\circ}}{360^{\circ}} \cdot \frac{3 \times 10^{8} \text{ m/sec}}{4000 \text{ Hz}} = \underline{28.1 \text{ km}}$$

As has been inferred earlier, the mentioned measurement technique would only be accurate as long as the two signal sources remained at exactly the same frequency during the time the aircraft moved away. This is because some of the accumulated phase difference measured at

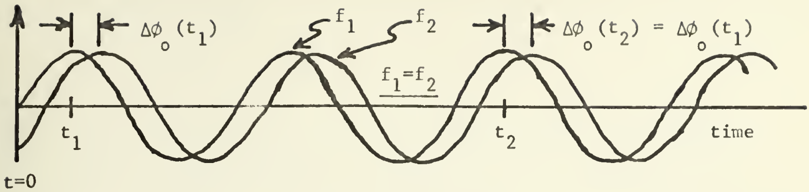
the new range relative to the initial range would be due to change of frequency of one of the signal sources and not due to the change in range. This can be better understood if the inter-relationship between phase and frequency is considered.

The most generally accepted definition of instantaneous frequency as a function of time [Ref. 5] for a signal is given by:

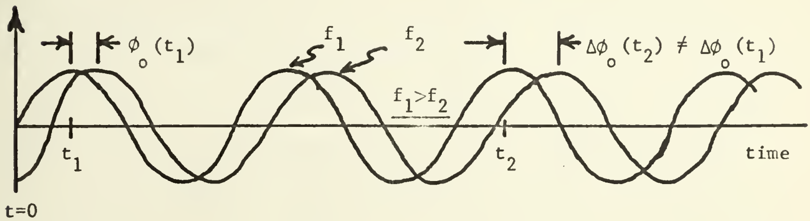
$$f(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt} \; ; \quad \text{where } \phi \text{ is the instantaneous phase of the signal in radians.}$$

For two signals fixed in space with the same frequency, their phase difference will remain constant for all time as shown in Figure 3(a). If one of the signals is slightly different in frequency, however, their phase difference at a later time is no longer the same, as is shown pictorially by the exaggerated frequency difference of two sine-wave signals in Figure 3(b).

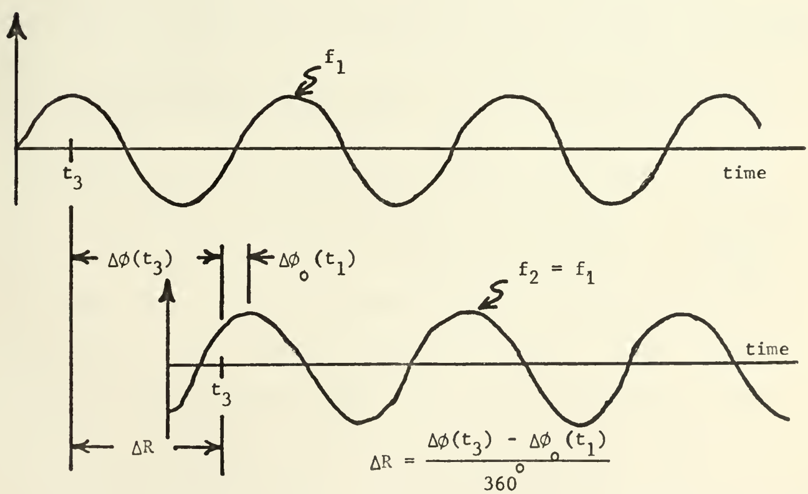
For the situation of two signals which are <u>not</u> fixed in space (as in the case of the ranging signal and the aircraft reference signal), the accumulated phase difference would be due to the change in range between the two signal sources only as long as both sources remained at the same frequency. This condition is shown in Figure 3(c) where, at time t_3, the two signal sources have changed relative position in space by a distance ΔR. A value for ΔR is determined by subtracting the phase difference $\Delta\phi_o$, (determined at the zero range reference position as shown in Figure 3(a)) from the phase difference $\Delta\phi(t_3)$, (determined at the new position), and then relating the result to a range value by means of the fractional wavelength traveled during time interval $\Delta t = t_3 - t_1$. To be exact:



(a) Two signals of same frequency fixed in space (say at zero range) with phase difference $\Delta\phi_o$.



(b) Two signals of different frequencies ($f_1>f_2$) which are fixed in space.



(c) The two equal signals of (a) shown at time, t_3, separated in space since time t_1 by a distance ΔR.

THE EFFECT OF FREQUENCY INSTABILITY

FIGURE 3

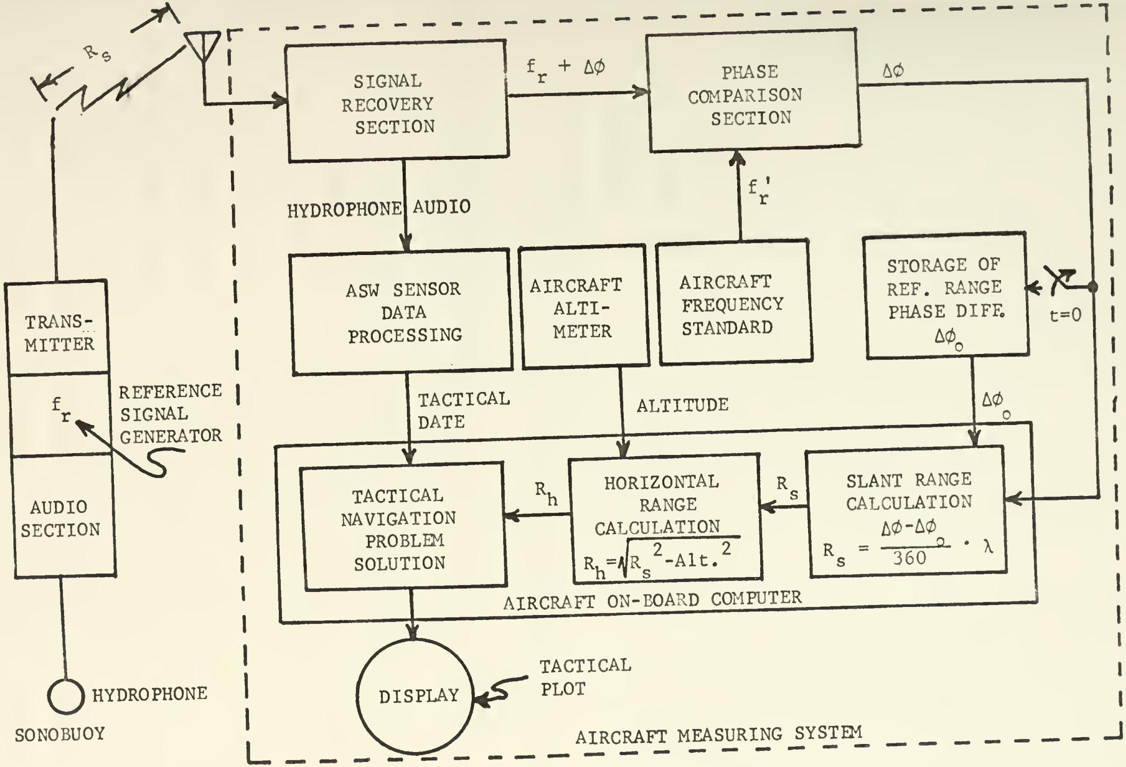
$$\Delta R = \frac{\Delta\phi(t_3) - \Delta\phi_o(t_1)}{360^o} \cdot \lambda$$

Hence, from the comparison of the above three cases, it is apparent why a measured phase difference is only valid as a range reference in this ranging concept as long as the two signals remain stable and equal in frequency.

B. DEVELOPING CONCEPTS FOR A RANGING SYSTEM

Utilizing slant range from the sonobuoy, determined in the manner described above, and combining it with the known aircraft altitude, the resulting geometric problem could be solved for the horizontal range value by a system as shown in Figure 4. The newer models of ASW aircraft have an on-board computer. Therefore, the computation of slant range and horizontal range could most easily be made by providing the phase difference measurement and the aircraft altitude as inputs to the computer for the calculations. Provision must be made to store the phase difference measurement ($\Delta\phi_o$) obtained at the known initial range so that this value may be applied to all slant range calculations made at any later time to obtain a correct value for the instantaneous slant range. This initial measurement might be made before the buoy is dropped (at known zero range) or later when marking on top of the buoy visually (at known altitude range). The choice would mainly be determined by the feasibility of turning on the ranging signal before the buoy leaves the aircraft and by tactical considerations. This will be discussed further in a later chapter.

For some aircraft it might be more advantageous to develop a small, separate analog computer to perform the computations. In either case,



FUNCTIONAL DIAGRAM OF A PHASE-DIFFERENTIAL RANGING SYSTEM

FIGURE 4

the actual computations of the horizontal range values are most easily handled as a separate computational problem for a computer. When implementing the system into hardware, the output of the phase measuring system would have to be interfaced to a computer of either the analog or digital type. With this in mind, the computational section of the proposed system would be a problem for the computer engineer and programmer. It will only be considered, therefore, as a functional block as shown in Figure 4 during remaining discussions of the system in this report. This decision to "black box" the computational section reduces the design and evaluation of the system to the first few blocks shown in Figure 4 consisting of the following components and subsections:

1. Sonobuoy
    a. Generation of ranging signal.
    b. Transmission of ranging signal by sonobuoy transmitter.
2. Aircraft Measuring System
    a. Recovery of the ranging signal.
    b. Phase-comparing the ranging signal to the reference signal.
    c. Range computation from the phase difference measurement.

Before discussing, in detail, the functions of the conceptual blocks listed above, consideration must be given to the design factors of both the sonobuoy and the aircraft sections of the system. In addition, a good understanding of frequency stability effects on the accuracy of the ranging system being designed must be presented before a method of generating the ranging signal in the sonobuoy is considered. These items are discussed in the following chapters before proceeding to the design and evaluation of the prototype system that was constructed in this project.

III. MODIFYING THE SONOBUOY FOR THE RANGING SYSTEM

Before a design modification of the sonobuoy for the ranging system can be undertaken, a number of considerations must be made, including the manner in which present production models of sonobuoys are designed and the factors limiting any design modification.

A. DESCRIPTION OF THE ASW SONOBUOY

Present day ASW sonobuoys have had their design and packaging fairly well standardized. This is by necessity to fulfill the MILSPEC requirements set forth by government contracts. It is also due to the fact that all sonobuoys must be compatible with the dispensing system of all current models of ASW aircraft.

The sonobuoys in current use are almost all identical in packaging. The only major differences are in the circuitry that actually goes into the sonobuoy, which is dependent on the function and mission of the particular model of sonobuoy and varies from one manufacturer's model to the next. For that reason, a description of the Sonobuoy AN/SSQ-57 will be given as an example of the typical construction of all sonobuoys. The SSQ-57 sonobuoy was the model used as the test bed for the prototype sonobuoy ranging system designed in this project. Much of the descriptive material on the SSQ-57 which follows was obtained from Ref. 6.

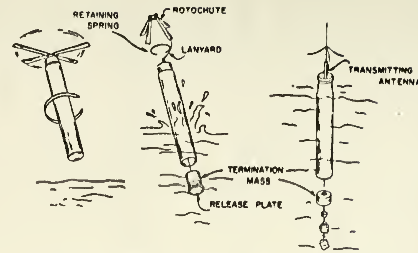
The SSQ-57 is a single unit contained within a cylindrical aluminum housing. It is approximately 36 inches long, 4-7/8 inches in diameter and weighs about 19-3/4 pounds. When expended by the aircraft at altitudes from 150 feet to 10,000 feet and at speeds from 150 to 250

knots, its free fall is retarded by a rotochute which is deployed after leaving the aircraft and is ejected on water impact. Figure 5 shows the sequence of operation.

Once in the water, a self-contained, sea-water-activated battery powers the sonobuoy circuitry, which detects and amplifies underwater sounds obtained from a hydrophone that is deployed on a 95-foot cable. The amplified underwater sounds are used to modulate a self-contained FM transmitter which transmits the signals to the aircraft. A FM receiver on the aircraft detects the signals for analysis and display by ASW processing equipment. By this means, the location and identification of the underwater sound sources are obtained.

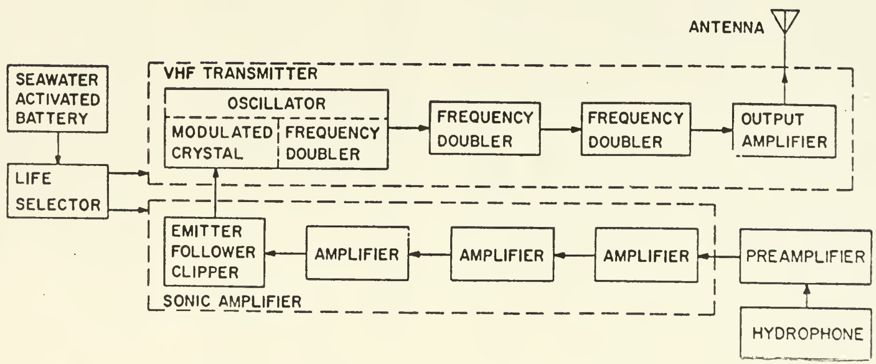
A block diagram of how the sonobuoy functions is shown in Figure 6. The frequency modulation is achieved by varying voltage across a voltage-variable capacitance diode (VARICAP), which in turns varies the frequency of a crystal oscillator. The frequency-modulated signal is then put through three doublers to get the carrier frequency up to the 162.25 to 173.50 MHz frequency band. Transmission is via a quarter-wave dipole antenna which is erected at time of water impact. The sonobuoy may have a lifetime of 1 or 8 hours as selected prior to launch. The sonobuoy hull has a water-soluble plug which disolves and scuttles the buoy in 8 to 20 hours so that it is not a hazard to the navigation of surface vessels after its useful life.

A complete schematic diagram of the sonobuoy is shown in Appendix (A). The general configuration of the SSQ-57 sonobuoy construction can be observed in the photographs of the packaged prototype sonobuoy section contained in Appendix (G).



SONOBUOY SEQUENCE OF OPERATION

FIGURE 5



SONOBUOY AN/SSQ-57 FUNCTIONAL BLOCK DIAGRAM

FIGURE 6

B. DESIGN LIMITATION FACTORS

Numerous sonobuoys are carried on ASW aircraft and are expendable items. Although their unit price is not high, expending them in large quantities runs into great cost. Anyone designing a modification to the present sonobuoy design to implement a sonobuoy ranging system must therefore keep the cost increase factor under prime consideration.

The large number carried on board an aircraft requires that the size and weight of sonobuoys be kept as small as possible. Any modification being considered should be contained within the cylindrical hull of the present sonobuoy package in order to remain compatible with existing aircraft dispensing systems. Any increase in the overall sonobuoy weight, due to a modification, must remain less than 1 or 2 pounds so that the floatation stability of the sonobuoy is not affected adversely.

The prototype system designed in this project was created with the intention of being able to retrofit the sonobuoy modification section into past production sonobuoy models. This is a cost-saving feature since large inventories of past production models would not be wasted by having to create a completely new sonobuoy model for the sonobuoy ranging system.

Since the salt-water-activated battery in the sonobuoy has a definite lifetime and a limited power capability, any additional power consumption caused by a modification to the sonobuoy must be kept to a minimum. For this reason, and due to an additional saving in size and weight, maximum use was made of integrated circuits (ICs) in the design of the prototype system of this project. The present state of the art of integrated circuit production has reduced the price of ICs to a

point where consideration of their small increase in cost over discrete components is outweighed in this application by the savings in weight, size, and power consumption.

Even with maximum use of integrated circuits, the increase in power required by the sonobuoy modification section designed in this project turned out to be high. This was primarily due to the unavailability of low-powered oscillators that have adequate frequency stability to fulfill the range accuracy requirements of the system. This will be discussed further later in this report. From these considerations, it became evident at an early stage that a price to be paid for satisfactory frequency stability (at least under the present state of the art) was high power consumption.

It was necessary to determine the amount of excess energy available in existing sonobuoy batteries for powering any additional modification circuitry. In order to see how restrictive the power limitation factor was going to be, the following tests were conducted.

1. <u>Testing the Power Requirements of a SSQ-57 Sonobuoy</u>

This test was done by connecting laboratory power supplies to a SSQ-57 sonobuoy in place of the battery and then measuring the current drawn at the rated voltages of the battery. The battery for the SSQ-57 supplies two positive voltages to the circuitr[illegible] 10.1 Vdc for powering audio and RF circuitry, and 1.5 Vdc to power ti[illegible]r circuitry which controls the lifetime of the buoy. The results of this test, under conditions of both 8 hour and 1 hour lifetime settings, are shown in Table I.

2. <u>Testing the Power Capability of a SSQ-57 Battery</u>

The second test was to determine the effect of adding a modification package to the sonobuoy circuitry. This was done by using

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TABLE I

POWER CONSUMPTION TEST RESULTS

SSQ-57 Sonobuoy, Channel 16, Serial No. 2745

Lifetime Setting	Current drawn @ Terminal Voltage	Power Consumed
8 Hours	250 mA @ 10.1 Vdc	2.530 WATTS
	6.5 mA @ 1.5 Vdc	0.097 WATTS
1 Hour	250 mA @ 10.1 Vdc	2.530 WATTS
	125 mA @ 1.5 Vdc	0.187 WATTS

the power requirements of the signal generation section of the prototype system constructed in this project as an example. It was determined that the modification package of the prototype system required a maximum of 550 milliamps at 10,1 volts, or 5.55 watts of power. The majority of this power (approximately 3.54 watts) was required only for short periods of time to power the ovenized, temperature control section of the crystal oscillator. Since the oven drew the majority of its power only at the start of operation when bringing the temperature up to operating temperature, 5.5 watts can be considered as the absolute worst case condition. Using this with the data from Table I, dc load values for the battery simulating a combination of the existing circuitry and the modification package were arrived at as follows:

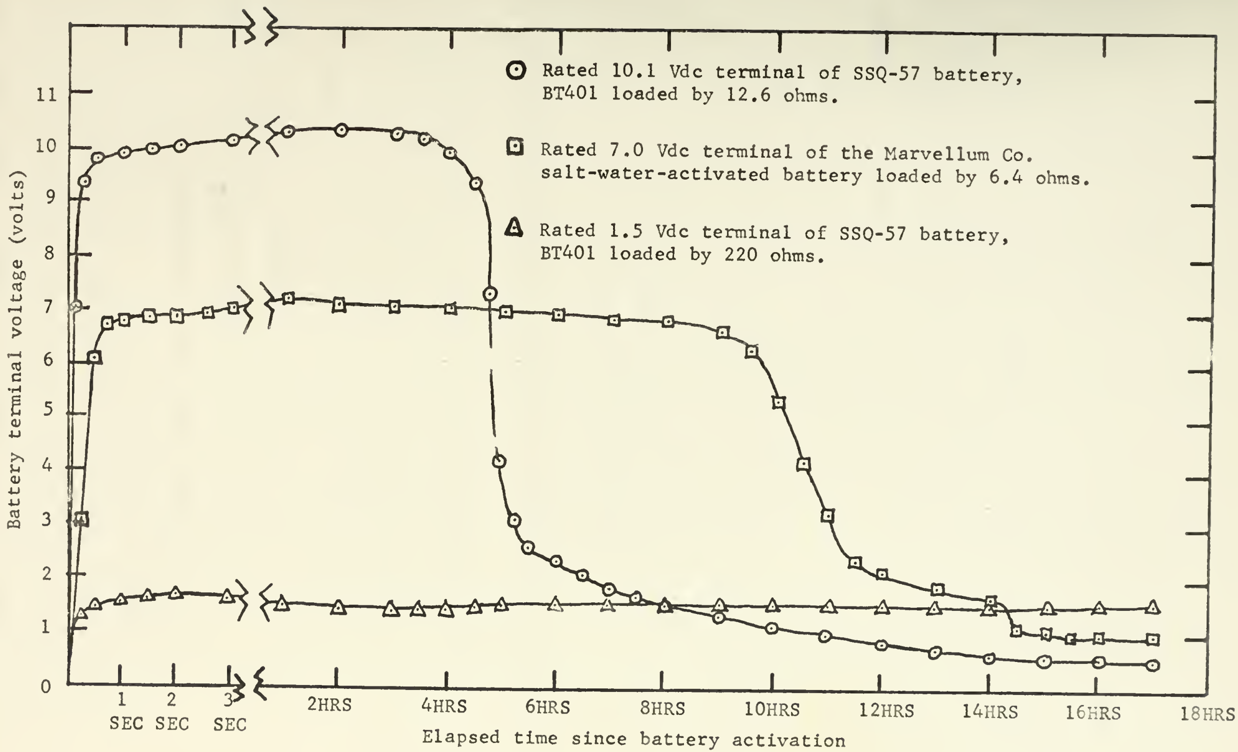
Power Consumed by SSQ-57 at 8 hour lifetime setting	=	250 mA @ 10.1 Vdc 6.5 mA @ 1.5 Vdc	= 2.53 watts = 0.097 watts
+		+	+
Power Consumed by modification package	=	550 mA @ 10.1 Vdc	= 5.55 watts
Total power Consumed at 8 hour lifetime setting	=	800 mA @ 10.1 Vdc 6.5 mA @ 1.5 Vdc	= 8.08 watts = 0.097 watts

$$\therefore \text{ dc load for 10.1 Vdc} = \frac{10.1 \text{ Vdc}}{0.8 \text{ amp}} = \underline{12.6 \text{ ohms}}$$

$$\text{dc load for 1.5 Vdc} = \frac{1.5 \text{ Vdc}}{0.0065 \text{ amp}} = \underline{230 \text{ ohms}}$$

These two loads were placed across a Model BT 401 battery (obtained from an SSQ-57 Sonobuoy) which was activated by immersing it in the ocean at pierside. The two voltages across these two loads were continuously recorded versus time to determine the useful lifetime of the battery under the simulated additional load of the modification package. A plot of these voltages versus time is shown in Figure 7. It was observed that both voltages came up to full rating in a few seconds after immersion. The 10.1 Vdc voltage remained at or above rated value for 3 hours and 6 minutes. It then discharged slowly, providing useful voltage for one additional hour, and then discharged rapidly to unuseable voltage levels in less than 30 minutes. The 1.5 Vdc voltage remained at or above the rated value for the duration of the test (17 hours and 12 minutes). This was understandable since very little current was being drawn by the timer circuitry during the simulated condition of an 8-hour lifetime setting.

As mentioned above, the power required by the sonobuoy modification package was fairly high, primarily due to an oven which temperature stabilized the crystal oscillator for optimum frequency stability. It was understandable that this package would degrade the useful life



LIFETIME TESTS OF TWO SALT-WATER-ACTIVATED BATTERIES WITH A LOAD SIMULATING A SSQ-57 SONOBUOY AND AN INSTALLED MODIFICATION PACKAGE

FIGURE 7

of the SSQ-57 battery by almost half of the normally rated 8-hour lifetime, since the amount of power drawn was more than doubled. The energy capacity of the battery would not be such a limiting factor if this oscillator could be replaced with one requiring must less power.

Since power limitation appeared to be one of the most critical design factors in this project, a thorough search for the most stable, low-powered oscillators available on the industrial market was made. Temperature-compensated crystal oscillators (TCXOs), which consume very little power, were considered for the reference signal source at one point in this project. However, the model of TCXO obtained was not sufficiently stable in frequency to fulfill the accuracy requirements of the system (this will be discussed later in this report). The state of the art of designing TCXOs is being advanced almost monthly by use of modern computer-aided design techniques [Ref. 7, 8, 9, & 10]. It is therefore possible that in a matter of a few years a TCXO with adequate stability will be available which will fulfill the accuracy needs of this project. With the low power consumption of the TCXO the power limitation factor would not then be so crucial, and the power requirements could be fulfilled by existing sonobuoy batteries.

Alternative solutions to the power limitation problem would be to place two smaller batteries in the buoy or obtain a high-energy battery which could fulfill the additional power requirements. It was not certain whether batteries of high enough energy were available in small enough size. Therefore another model battery of approximately the same size and design as the SSQ-57 battery, but of a higher advertised energy capacity, was obtained for testing. This battery was tested in the same manner with a 6.4-ohm load across its 7.0-Vdc output so that

approximately the same power would be supplied. A plot of its voltage versus time is also plotted on Figure 7 so that a comparison can be made to the SSQ-57 battery. This test indicated one significant point: it is technically feasible to construct a salt-water-activated battery of small enough size which can handle the power requirements of the system being considered. It therefore appeared that the easiest solution to the power limitation problem would be to specify a new battery with the proper terminal voltages which would replace the present battery at the same time that the modification package for the sonobuoy ranging system is retrofitted into a sonobuoy.

Models of batteries tested in this project may be procured through the Navy Supply System using the information given in Table II.

TABLE II

BATTERY IDENTIFICATION INFORMATION

Type Battery	Ordering Information
BT-401	FSN 613-164-8753 (IN-Cog Item)
Marvellum Co. Battery	Contract NOW 64-0319-F(9/65) Contract No. Mfr. 538016-1

One other alternative is also possible. In recent years since the advent of multi-purpose satellites, there have been major advances in the design of small, low-powered crystal ovens for application in satellite frequency-control instrumentation. In one case an oven has been designed which consumes less than 159 milliwatts (compare this to the 3.54 watts of the prototype's oven) and is less than 5.2 cubic inches in volume, with expressed confidence of reducing the power

consumption and size even lower in the very near future [Ref. 11]. This is a low enough power level that the present battery would be able to handle the additional load due to a modification package with a signal generator that uses one of these ovens.

IV. EFFECTS OF FREQUENCY STABILITY

It has already been emphasized that the accuracy of the sonobuoy ranging system being considered is dependent on the frequency stability of the frequency sources in the aircraft and the sonobuoy. There are many factors which can cause instability. Before discussing them, the meaning of frequency stability when used to describe the quality of a frequency standard must be defined.

A. DEFINING FREQUENCY STABILITY

There is still a great deal of disagreement in the field of frequency control on methods of specifying and measuring frequency stability [Ref. 11]. Various users of frequency sources still demand specifications in both the time and the frequency domain. However, it is generally accepted that there are two types of stability: long-term and short-term. Long-term stability refers to slow changes in average frequency with time due to secular changes in the resonator or other elements of the frequency standard being considered. Short-term stability refers to changes in average frequency over a time sufficiently short, (but greater than some specified minimum time) so that the change in frequency due to long-term effects is negligible. [Ref. 12] Short-term stability is an attempt to describe the amount of instantaneous frequency dispersion that occurs around the average frequency which is observed over the long-term effect.

Since no standardized definitions are available to describe the long-and short-term performance of frequency standards, other than in the general terms above, use will be made of three definitions used by

Grant [Ref. 4] to describe frequency effects. He used three terms which are also used by many manufacturers of oscillators and frequency standards: frequency offset, frequency drift, and frequency deviation. Each of these effects causes frequency error, which is defined as the difference between the actual instantaneous frequency, f(t), and the nominal frequency, f_o. It may be mathematically defined as:

$$\text{frequency error} = \Delta f = f(t) - f_o \ .$$

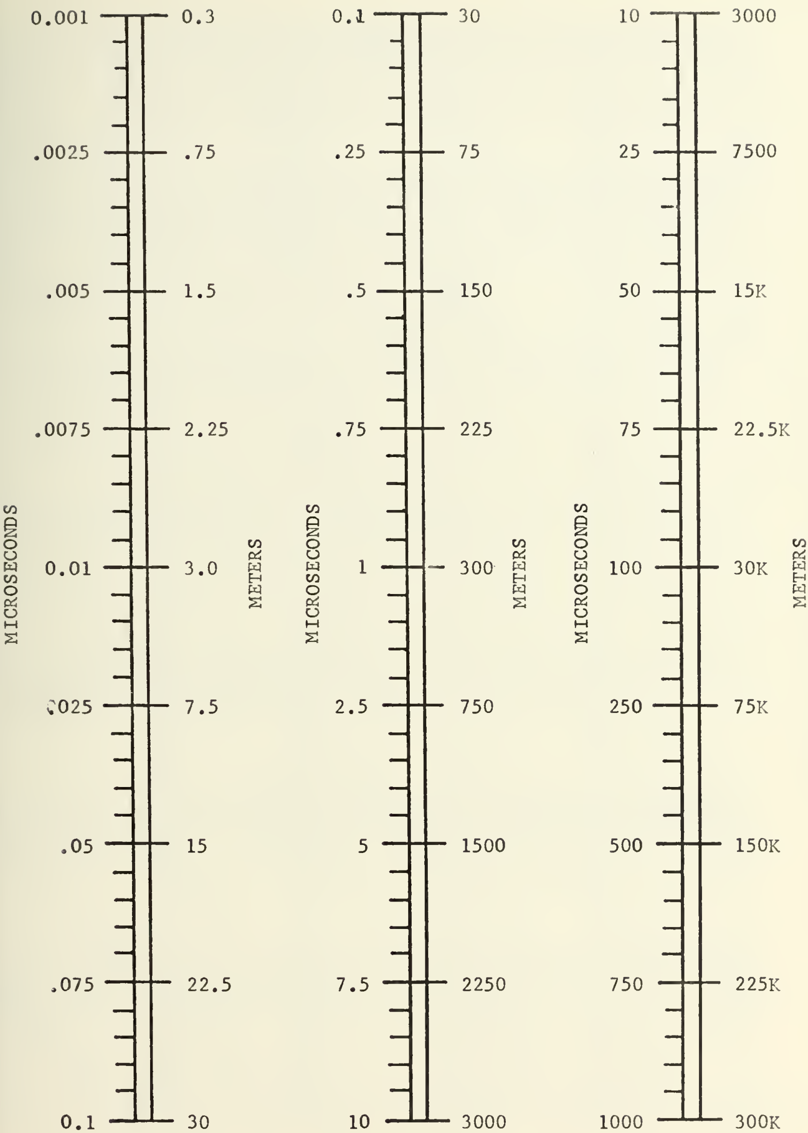
It is usually more convenient to consider time errors in frequency standards rather than frequency or phase errors. The three are related by a normalized quantity sometimes referred to as the fractional error as follows:

$$\frac{\Delta f}{f} = \frac{\Delta\phi}{\phi} = \frac{\Delta T}{T} \ ;$$

where
f = nominal frequency,
$\Delta\phi$ = phase error,
ϕ = instantaneous phase,
ΔT = time error,
T = duration of signal.

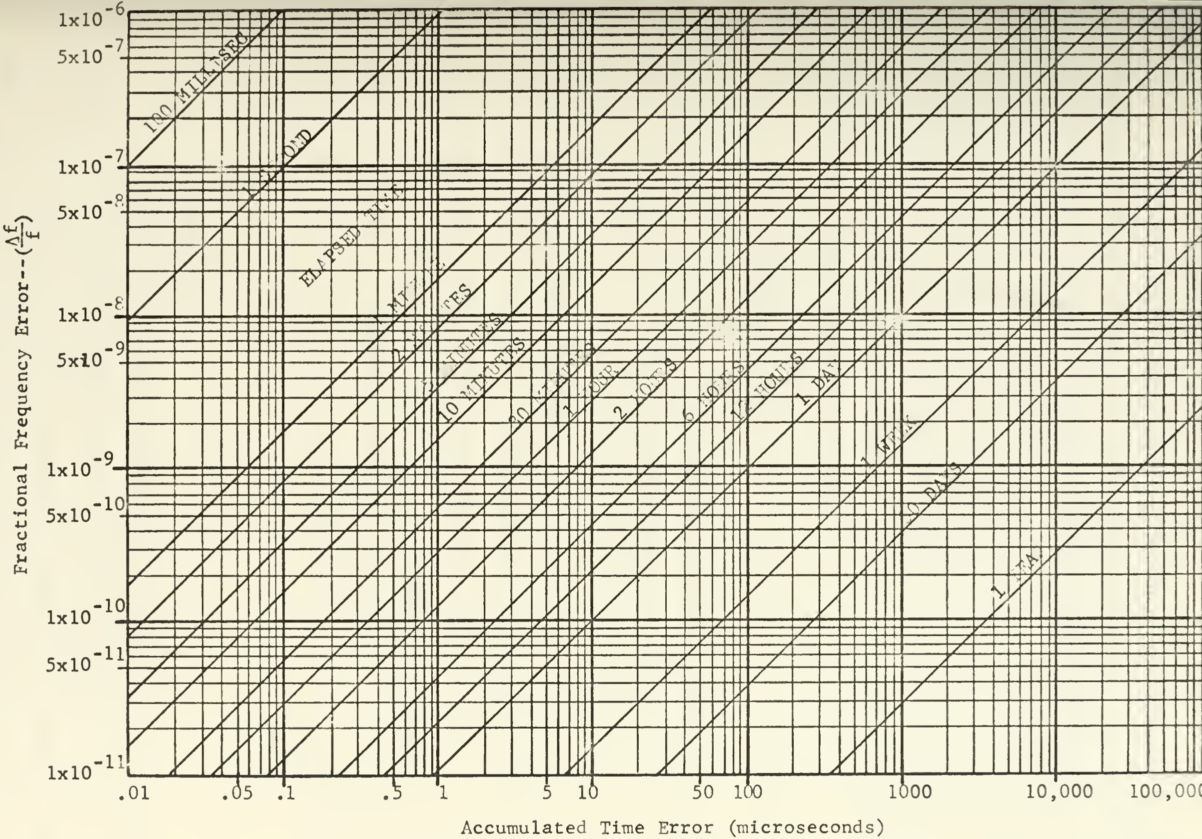
Time error can be converted to range error where the range is the distance a signal will travel at the speed of light during the time error, ΔT. The graph in Figure 8 facilitates a quick conversion between these two errors.

A general practice in the frequency-control field is to make use of a Frequency-Error Conversion Chart for quickly determining the actual fractional frequency error when the accumulated time error, ΔT, of a standard has been determined, or vice versa. One of these charts is shown in Figure 9. The use of this chart will be explained by referring to examples of offset, drift, and deviation when expressed as a fractional error.



CONVERSION CHART, ACCUMULATED
TIME ERROR TO RANGE ERROR

FIGURE 8



FRACTIONAL FREQUENCY-ERROR CONVERSION CHART

FIGURE 9

1. Frequency Offset

Frequency offset can be defined as the amount that the actual frequency differs from the desired or nominal frequency. It is neither a short-term nor a long-term stability effect, but rather an initial condition. For instance, if an oscillator was designed for a resonant frequency of 1 MHz, but when actually turned on it started operating at 1,000,001 MHz and remained precisely at that frequency, then the frequency offset would be +1.0 cycle out of 1,000,000 cycles. Expressed as a fractional error it would be:

$$\frac{\Delta f}{f} = \frac{1.0}{1,000,000} = 1 \times 10^{-6} \quad .$$

After one hour this offset would cause an accumulated time error which can be determined by using the chart of Figure 9. Entering this chart on the ordinate with 1×10^{-6}, moving horizontally to the 1-hour elapsed time line, and then moving vertically downward to the abscissa, the accumulated time error due to the offset is determined to be about 3600 microseconds. Multiplying this times the speed of light, 3×10^{8} m/sec, the accumulated time error converts to a range error of 1080 kilometers. This example shows that even though 1×10^{-6} seems like a tolerable value for an initial offset in the nominal frequency, it would make a phenomenally large error when used in any type of navigation system.

2. Frequency Drift

Frequency drift can be considered as a change in the frequency offset. It is generally thought of as a long-term stability effect inherent to oscillators using piezoelectric crystals for frequency control. The frequency drift is usually expressed as fractional error

measured over long periods of time such as 24 hours, weeks, or even years. In those oscillators using crystal control, the drift is due to the crystal aging. The crystal aging rate is usually constant after a sufficient warm-up period of from 10 minutes to days, depending on the design of the oscillator. Operating the crystal at higher temperatures, as in temperature-controlled ovens, tends to increase the aging rate and the drift will be higher.

As an example of frequency drift, consider an oscillator which is measured to be oscillating at a nominal 50 MHz after its initial warm up period. Six hours later it is measured to be oscillating at 50,000,000.2 Hz. This means that the oscillator has a drift expressed as a fractional error over 6 hours of:

$$\text{Drift} = \frac{\Delta F}{F} = \frac{.2 \text{ Hz}}{5 \times 10^{7} \text{ Hz}} = 4 \times 10^{-9}/6 \text{ Hours}$$

Before converting this to time error, it must be remembered that the average frequency stability over the six hours was one half the total drift. For an average drift of $2 \times 10^{-9}/6$ hours, Figure 9 shows this to be 46 microseconds accumulated time error in 6 hours. Expressing this time error into range error rate by means of the graph of Figure 8 gives a final range error rate of 13.8 kilometers/6 hours or 2300 meter/hour.

3. Frequency Deviation

Frequency deviation is a short-term stability effect which describes the dispersion of the instantaneous frequency from the nominal frequency due to undesired components of noise and spurious signals. It is usually defined as an average of the change of frequency over a

specified time interval which is sufficiently short so that there is no influence from any long-term effects such as drift.

When using deviation to describe the short-term frequency stability, the minimum observation time over which the frequency has been averaged must be specified. This is because short-term deviation is a statistical quantity which becomes infinitely large in dispersion as the observation time is made infinitely short, and which approaches the long-term average frequency as the observation time is made long. As the observation time becomes shorter and shorter, noise becomes the major cause of the deviation and gives the measured deviation more of a statistical nature.

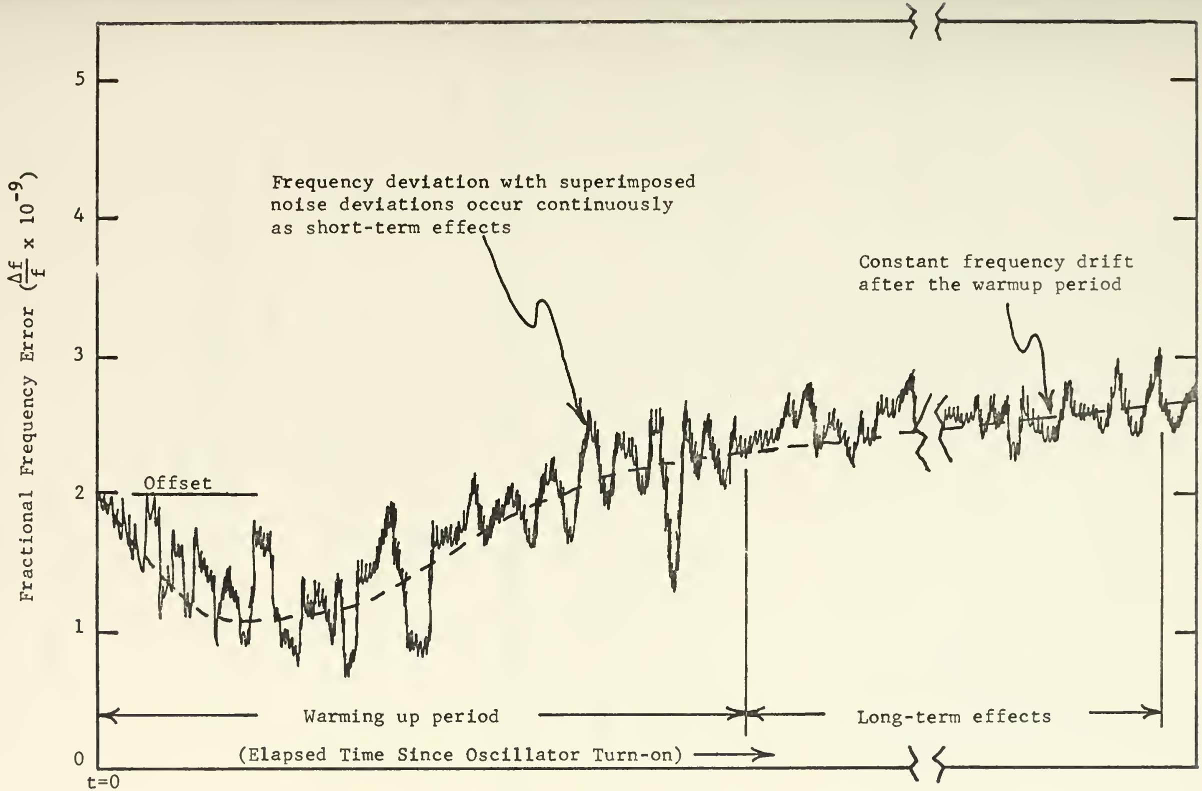
There has been a great deal of research done to determine the best methods of measuring short-term stability effects [Ref. 11,13,&14]. These will not be covered in this paper since short-term stability requirements are not as critical to the accuracy of the ranging system as long-term effects. The sources of frequency deviation are considered to be:

(1) Thermal noise in the oscillator circuitry which varies the resonance frequency.

(2) Additive noise associated with the remaining circuitry which does not change the resonant frequency but changes the spectral content of the signal by addition or subtraction.

(3) Fluctuations in the oscillator parameters, including such features as supply voltage, load, humidity, crystal parameters, and ambient temperature.

In summarizing the above definitions of stability, a good way to visualize their combined frequency stability effect is by means of the example plotted in Figure 10. The initial offset from the nominal frequency is shown to be $+2 \times 10^{-9}$. The frequency drift has necessarily



COMBINED EFFECTS OF FREQUENCY OFFSET, DRIFT AND DEVIATION

FIGURE 10

been shown to be much greater in magnitude then would normally be expected. This is so that the much smaller effect of the drift can be seen on the graph. The drift would be so slow after the warm up period that it would be undetectable on a true scale graph. The dotted line represented the average frequency. During very short intervals of time, noise effects are superimposed on the continuous, frequency deviation curve to emphasize that spectral content of a signal and the observation time does have a definite effect on the measured short-term stability.

B. FACTORS AFFECTING FREQUENCY STABILITY

The factors which affect frequency stability are many and varied. A thorough analysis of the cause and effects could be the subject of a report in itself. Kemper has written an article where he makes a concise description of all the characteristics of quartz crystals when used for frequency control [Ref. 15]. Grant gave a very thorough explanation of the temperature effects on crystal oscillators in his thesis and showed some excellent plots of their characteristics [Ref. 4]. In the interest of avoiding redundancy, these effects will be only briefly described and reference should be made to the above references for more specific information.

1. Temperature and Aging Effects on Crystal Oscillators

Temperature affects the frequency stability of crystal oscillators depending on the type of geometric cut used to manufacture the crystal. AT and GT cut crystals have the least dependence of frequency stability on temperature. AT crystals are normally preferred over the GT cut crystals for use in most frequency standards due to the physical size and high cost of GT cut crystals.

Aging is caused by some intrinsic materials, (either solid, liquid or gaseous) that transfer from the crystal plate to its surroundings, or that transfer to the plate from the surrounding atmosphere or its case. The rate of aging becomes relatively constant as all of the transfer of impurities reaches a steady state. High operating temperatures or driving levels make the aging rate much worse. Kemper explains the tradeoffs involved in selecting a crystal for the best frequency stability in any particular range of temperatures and in any particular frequency range. He points out that the 1 to 5 MHz frequency range exhibits the best aging characteristics, and that the best crystals with respect to their quality factor (Q) and their frequency stability with time are most easily manufactured in this range.

It will suffice to say that the adverse temperature and aging effects can be compensated somewhat by one or more of the following actions whem attempting to obtain the ultimate in frequency stability:

(1) Proper choice of the crystal cut and close tolerances in the manufacturing of the crystal.

(2) Temperature control of the crystal by temperature control ovens.

(3) Temperature compensation of the oscillator by thermistor/varicap networks which vary the capacitance of some parameter in the oscillator circuit in a negative feedback manner so as to maintain the frequency constant during temperature variations.

(4) Close controls in the impurity levels of materials used in the construction and packaging of the crystal.

2. Supply Voltage and Load Variation Effects

Any variation in the supply voltage powering the oscillator, either in the form of ripple, noise, or long-term variations, can cause change in the oscillator frequency. By proper voltage regulation of

the power supply and decoupling it from any high-frequency feedback paths, this degrading factor can normally be eliminated.

The capacitive loads in an oscillator circuit that may lie in series or parallel with the crystal unit can have a significant effect on the frequency of oscillation. Proper circuit design will normally eliminate this problem.

The capacitive load that is across the crystal in the oscillator circuit must be closely specified when ordering a crystal for the oscillator if it is desired to keep the frequency offset of the oscillator small. Sometimes variable capacitors can be used in series or in parallel with the crystal so that any offset that occurs when the oscillator is placed in operation can be tuned out. If the sensitivity of the frequency stability to temperature is desired to be low, the need for the temperature-insensitive elements in the oscillator circuit should be obvious.

After the oscillator is operating at the right frequency, any dynamic loads which have an impedance with a capacitive component can cause the oscillator frequency to change. The effect of a varying capacitive load can be compensated by decoupling the load from the oscillator by a buffer amplifier between the two.

3. <u>Shock and Vibration Effects</u>

Shock and vibration have three general effects on a crystal: temporary deviation which disappears instantaneously after removal of the stress; temporary deviation which disappears a few moments after the start of the stress, but may reoccur again later; and a permanent change of frequency or failure to oscillate when the stress is sufficient to physically damage the crystal or its plates.

The AT cut crystal is considered to be the least stress sensitive of the precision crystals, and indicates another reason why AT cuts are the most popular for the construction of frequency standards.

C. FREQUENCY STABILITY REQUIREMENTS FOR THE SONOBUOY RANGING SYSTEM

The definitions and effects discussed above may be applied to the signal sources of the sonobuoy ranging system. The range accuracy that is desired for the sonobuoy ranging system will determine the limits on the required frequency stability of the sources. In order to quantitatively determine these stability requirements, a few assumptions must be made concerning the desired instantaneous range accuracy and the maximum drift rate in range accuracy that is tolerable. If the tactics in ASW operations are analyzed, it appears that reasonable estimates for these values would be $\pm$ 50 meters instantaneous range accuracy and 100 meters/hour drift rate in range accuracy. The above estimates will be used to determine the approximate range of frequency stability that is required for a practical sonobuoy ranging system.

1. Long-term Range Accuracy Requirement

Assuming that the sonobuoy will only be used as a navigational reference for periods up to six hours, and assuming an accumulated range accuracy drift of 600 meters in the six-hour period (100 meters/hr.), then consider the following:

600 meters $\Rightarrow$ a time error of ΔT from Figure 8 = 2 microsecs,

If it is assumed that the frequency offset of the source is zero at $t = 0$, and if $\frac{\Delta F}{F}$ is the offset of the source after six hours, then:

$$\frac{\Delta f}{f} = 0 \text{ , at } t = 0 \text{ .}$$

$$\frac{\Delta f}{f} = \frac{\Delta F}{F} \text{ , at } t = 6 \text{ hours} = 21{,}600 \text{ seconds .}$$

$$\therefore \text{ average } \frac{\Delta f}{f} = \frac{\frac{\Delta F}{F}(t = 6 \text{ hrs}) + \frac{\Delta f}{f}(t = 0)}{2} = \frac{1}{2}\frac{\Delta F}{F}$$

$$\frac{\Delta F}{F} = 2 \cdot \text{average } \frac{\Delta f}{f} = 2 \cdot \frac{\Delta T}{T} = 2 \cdot \frac{2 \text{ microsecs}}{21{,}600 \text{ secs}}$$

$$\therefore \frac{\Delta F}{F} = 1.85 \times 10^{-10}$$

Drift has been defined to be the change in the frequency offset measured over a specified time. The quantitative value of the drift requirement for a satisfactory signal source to provide 600 meters/6 hours range drift accuracy is therefore given by:

$$\text{Drift} = \frac{\Delta F}{F} \cdot \frac{1}{T} = \frac{1.85 \times 10^{-10}}{6 \text{ hours}} = 7.38 \times 10^{-10} \text{ per day}$$

2. Short-term Range Accuracy Requirement

For two reference signals to be phase compared to determine accurate range, the measurement accuracy that is required to achieve the desired ± 50 meters of range accuracy must also be determined. Use of Figure 8 shows that 50 meters is equivalent to 0.161 microseconds of accumulated time error. Using this accumulated time error, the short-term stability of the signal sources for the sonobuoy ranging system must be at least:

$$\frac{\Delta f}{f} = 2.2 \times 10^{-7} \text{ per 1 second averaging time.}$$

From the above calculations it can be determined that the short-term stability requirement (2.2×10^{-7}/second) for obtaining ± 50

meter range accuracy is much less demanding than the long-term stability requirement (7.38×10^{-10}/day) for obtaining 100 meters/hour range drift accuracy. Oscillators with a short-term accuracy of 2.2×10^{-7}/ 1 second averaging time are not difficult to obtain at low power and small size. However, the long-term stability requirement of 7.38×10^{-10}/day is much more difficult to obtain at low cost and power consumption, both which are limiting factors when the oscillator is to be used in the expendable sonobuoy section of the proposed system.

The long-term stability requirement makes the use of a temperature-compensated crystal oscillator (TCXO) out of the question. State-of-the-art production of TCXOs using the most advance methods of computer-aided design have been able to achieve stabilities into the range of 1×10^{-7} to 1×10^{-8} at best, and then only at high cost. With a relaxation of the range drift accuracy requirement from 100 meter/hour to 500 meters/hour, the long-term stability requirement is reduced from 7.38×10^{-10}/day to 3.7×10^{-9}/day, which is approaching a range where oscillators are currently available with sufficient stability and at reasonable cost, power consumption and size to be used in the sonobuoy ranging system.

When this point was reached in the pursuance of this thesis, a major decision had to be made in light of the above stability limitations as to whether the concept for a sonobuoy ranging system was currently feasible. It is generally felt throughout the field of frequency-control technology, that major breakthroughs in frequency control of small, low-powered oscillators are soon to come. This is mainly due to technical fallout from the space program and to greater and greater use of computer-aided design techniques. If the sonobuoy

ranging system can be thoroughly developed, tested and evaluated using currently available oscillators in the sonobuoy at reduced range accuracies for the present time, then these later improvements in frequency control technology could be used to bring the developed system up to desired accuracies. Used at the present accuracy capability with currently available signal sources, it would still provide a secondary tactical navigation system for ASW aircraft which, when combined with other tacitcal navigation systems already in use, should provide a great deal of navigational assistance and overall improvement of tactical effectiveness.

With the above thoughts in mind, the physical construction of a prototype sonobuoy ranging system was pursued with one additional design criterion--easy replacement of the signal source in the sonobuoy section without requiring major changes to the remaining part of the system.

V. GENERATING THE RANGING SIGNAL IN THE SONOBUOY

If it is assumed that some means of generating a satisfactory ranging signal in the sonobuoy is available, there still remains the problem of transmitting the signal to the aircraft. Grant concluded that the most practical method was to generate the reference signal separately and use it to frequency modulate the sonobuoy's carrier oscillator for transmission to the aircraft [Ref. 4]. This requires that the signal be of a frequency within the pass band of the sonobuoy's FM transmitter. That band of frequencies is in the audio range where frequency stability is difficult to obtain unless the signal is derived by frequency dividing a much higher frequency of good stability.

Another alternative was to use the carrier oscillator of the sonobuoy's transmitter as the signal source. Since each of the 31 sonobuoy channels has a different frequency, this approach would require 30 different reference frequencies in the aircraft against which the phase comparisons could be made. In addition, a problem arises out of the fact that the carrier oscillators are frequency modulated by the hydrophone audio. This varies the frequency of the carrier and makes it impossible to use it as a stable signal source. However, if certain channels could be selected as the reference frequencies, the audio sections could be removed from those particular buoys and they could serve as special ranging system buoys. The remaining channels, with the original audio sections intact, could be used in the normal manner. The main reason for considering this approach and disregarding the

disadvantages was the possibility of reducing the cost, weight, and power consumption that would be required to implement a sonobuoy ranging system.

A. THE SONOBUOY CARRIER AS THE RANGING SIGNAL SOURCE

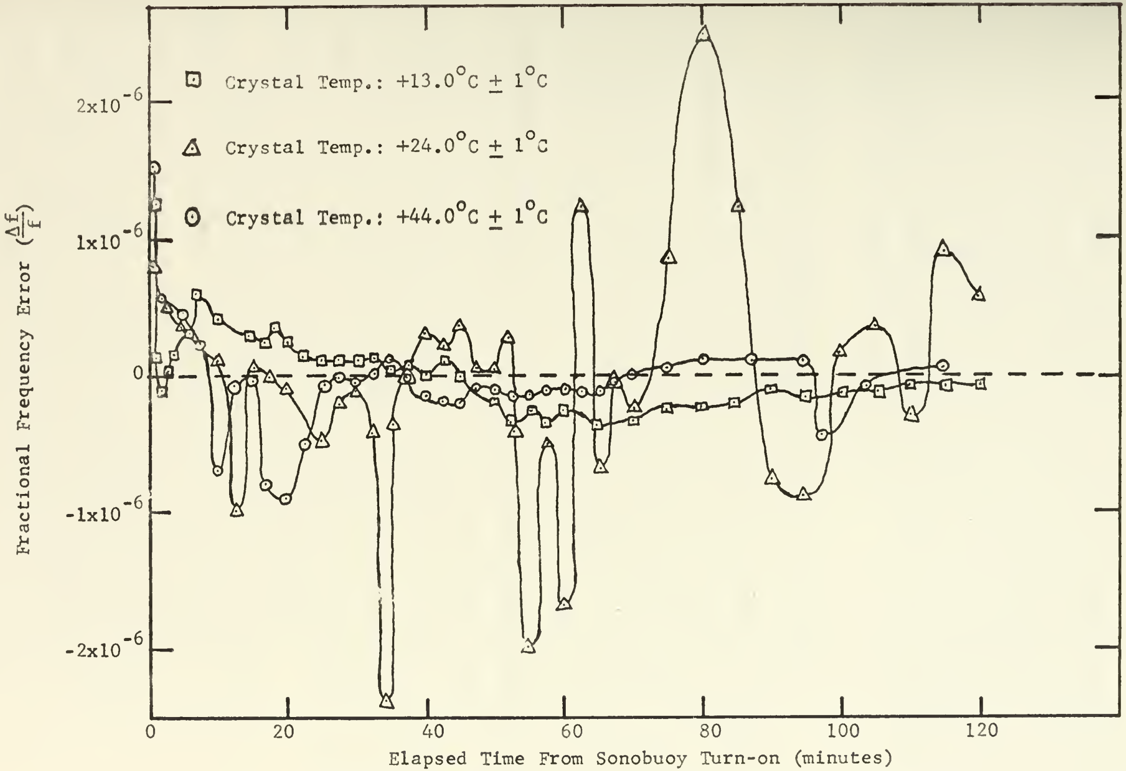
If the sonobuoy's carrier was going to be used as the signal source, it was obvious that the carrier oscillator would have to be placed under temperature control to obtain the required long-term frequency stability. It did not appear feasible to compensate the oscillator circuitry for temperature due to the nature of the sonobuoy's circuitry and due to the high stability requirement over the wide range of temperatures to be encountered in the sonobuoy's operational environment (approximately $0^{o}C$ to $+50^{o}C$).

To test the feasibility of achieving the required stability by temperature control, the entire sonobuoy circuitry was placed in a temperature-controlled environment for three frequency-stability tests at three different nominal temperatures. The audio section of the sonobuoy was disconnected for these tests. After the sonobuoy was turned on, the frequency of the sonobuoy oscillator was recorded using a frequency counter with a 10-second gating period. The counter used a Rubidium Atomic Standard for its time reference. Readings were recorded at the end of every other gating period for the first hour of operation. When the counts of the two consecutive gating periods were different, the value which was recorded was the average of the two. After one hour of operation it was presumed that the frequency had stabilized to approximately constant drift. Thereafter, readings were taken every five minutes. The value that was recorded was the average

of the six readings taken during the fifth minute of each recording interval. Temperature in the temperature-controlled cavity was closely monitored throughout the tests by thermocouples. The temperature of a thermocouple attached to the crystal case was recorded every five minutes.

To obtain a more meaningful description of the stability of the sonobuoy's carrier oscillator, it was desired to convert the observed frequency readings to fractional frequency error. The frequency error of each recorded frequency reading was obtained by subtracting the reading from the nominal frequency of the carrier oscillator. The frequency error was then normalized into fractional frequency error by dividing by the nominal frequency. The fractional frequency error was then plotted versus elapsed time since sonobuoy turn-on. The results of the three tests are shown in Figure 11.

It was noted in these tests that the temperature of the crystal case never varied by more than one degree centigrade. Although the temperature was closely controlled and power supply voltages were regulated, the carrier oscillator frequency varied considerably at all three temperatures. The variations appeared to be greater at room temperature than at low or high temperature, possibly indicating that the crystal's temperature coefficient curve [Ref. 4] did not cross the zero-frequency error axis near room temperature. The frequency offset at the start of oscillator turn-on was above the nominal frequency in all three tests. There was some indication of a stabilizing aging rate after the first 20 to 30 minutes of operation, with a relatively constant drift after that warm-up period.



FREQUENCY STABILITY TEST OF A SSQ-57 SONOBUOY TRANSMITTER

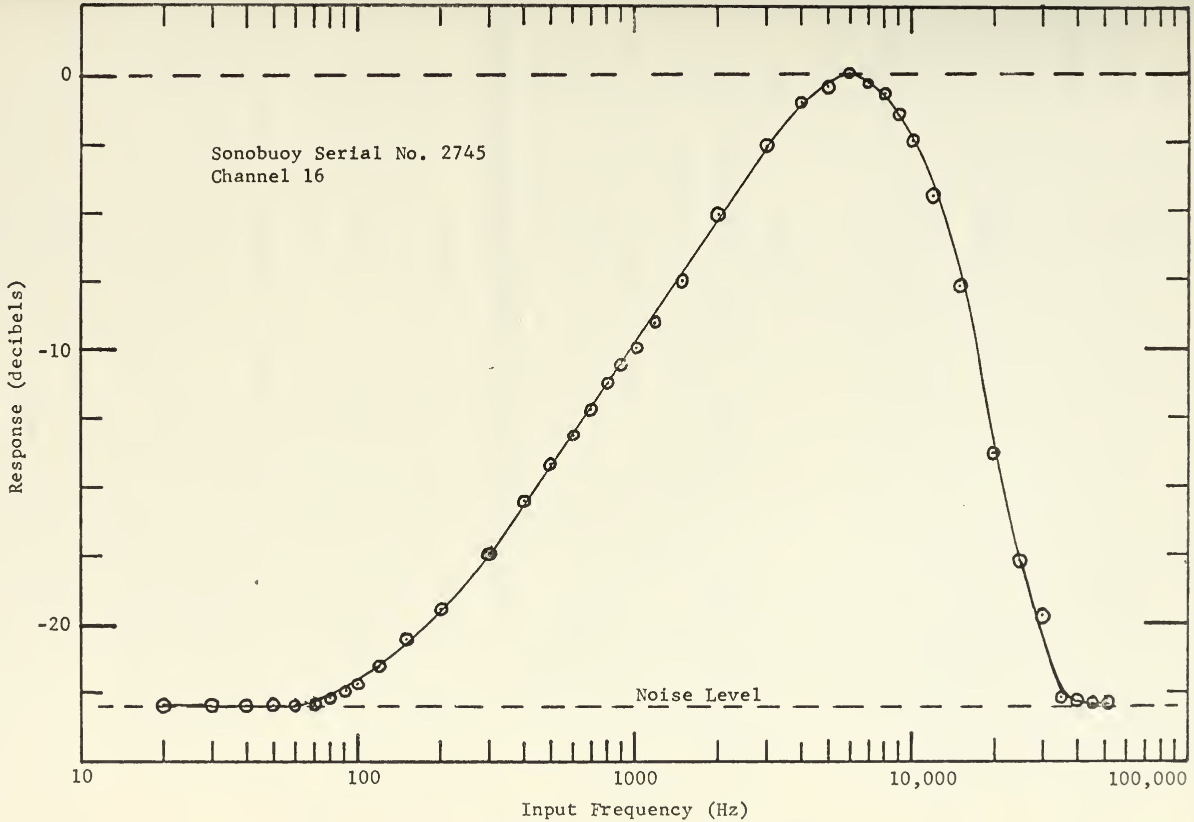
FIGURE 11

The major conclusion drawn from the above tests was that the sonobuoy's carrier oscillator was not sufficiently stable to be used as the ranging signal source even if it were placed under temperature control in an oven. The deviations were as high as 2.5×10^{-6} for periods up to 5-8 minutes. This would create too much accumulated time error, and hence range errors too large for use in the ranging system. The decision was made to return to the original idea of generating the ranging signal separately in the sonobuoy.

B. GENERATING A SEPARATE RANGING SIGNAL IN THE SONOBUOY

Grant selected a 4-kHz signal as the ranging signal frequency. He determined that this fell at the upper end of the pass band of the SSQ-41 Sonobuoy with which he was working. Since the SSQ-57 Sonobuoy was used as the test bed in this project, a test to determine its pass band was conducted. This test was performed by connecting an audio oscillator to the input of the audio amplifier of the sonobuoy through the test plug of the sonobuoy. The 9-pin test plug is shown on the schematic of the SSQ-57 sonobuoy in Appendix (A). The audio input was transmitted to an AN/ARR-58 radio receiver and the detected frequency response at the output of the FM discriminator of the receiver was recorded as the audio oscillator frequency was varied.

A plot of the frequency response obtained for the pass band of the SSQ-57 transmitter is shown in Figure 12. From this plot it was observed that a 4-kHz signal would be slightly below the center of the pass band. A check of pass band specifications in the handbooks for various other models of sonobuoys besides the SSQ-41 and the SSQ-57 indicated that 4-kHz would be a good choice for the frequency of a standardized ranging signal source for use in <u>all</u> sonobuoy models.



PASS BAND RESPONSE TEST FOR A SSQ-57 SONOBUOY

FIGURE 12

Grant determined in his work that the stability of the detected modulating signal used to frequency modulate the sonobuoy carrier was independent of the frequency of the carrier oscillator. A test to verify his observation was performed by placing the sonobuoy crystal in an oven and varying the temperature while transmitting an audio signal. The stability of the received audio signal was confirmed to be independent of the temperature variations and the frequency variations of the carrier.

C. FREQUENCY DIVISION

After making the decision to generate the ranging signal separately in the sonobuoy, it was obvious that some method would have to be used to divide the original frequency of the signal source down to a frequency within the pass band of the sonobuoy's transmitter. As was pointed out earlier, the best frequency stability is obtainable at higher frequencies, normally in the 1 to 5 MHz range.

Frequency conversion to a lower frequency by mixing action with a local oscillator would not be satisfactory because the stability of the resulting frequency would be dependent on the frequency stability of the local oscillator, thereby requiring <u>two</u> stable oscillators. For this reason a technique of frequency dividing by means of integrated-circuit down counters was used. The use of integrated-circuit down counters is finding increasing application in the field of frequency control, not only in the technical industries, but also by amateur radio operators and experimenters [Ref. 16 & 17].

The choice of 4 kHz as the final ranging signal frequency dictated that either an exact choice of frequency for the original source would

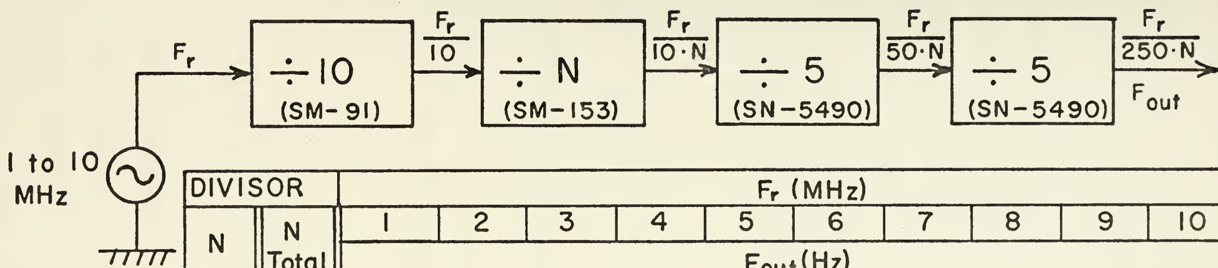
have to be made, or else some means would have to be provided to control the frequency division for dividing various frequencies down to 4 kHz.

It was not certain what oscillator was going to give the best frequency stability, and the source frequency therefore was not fixed. For this reason it was desirable to design the frequency divider so that any integer frequency from 1 MHz to 10 MHz could be used as the source frequency and could then be divided down to 4 kHz.

The above difficulty was resolved by using a relatively new product to the field of integrated-circuit frequency counters: the programmable frequency divider. By using one of these special counters, which can be controlled by properly applied voltages to some of its terminals, it is possible to make the divisor of the input frequency any integer between 1 and 10. Combining one of these counters with three other decade counters it was possible to cascade them into a divide-by-10, divide-by-5, and divide-by-5 frequency-division network. This is shown by the block diagram and divisor table in Figure 13.

The first counter in the chain was a Sylvania Decade Divider, SM-91, which is a counter designed to be used as a decade frequency divider. It has a special pulse-forming network on one input so that it will accept either a.c. or digital input signals if proper connections are made to the inputs. A double-pole, double-throw switch was included so that the frequency divider network could be used to divide either a.c. or digital sources by switching to the correct inputs.

The second counter of the network was the special Sylvania device called a Decade Programmable Frequency Divider, SM 153. It has four terminals which can be programmed by applying voltages in the correct



DIVISOR		F_r (MHz)									
N	N Total	1	2	3	4	5	6	7	8	9	10
		F_{out} (Hz)									
1	250	4000	8000	12,000	16,000	20,000	24,000	28,000	32,000	36,000	40,000
2	500	2000	4000	6000	8000	10,000	12,000	14,000	16,000	18,000	20,000
3	750	1333	2666	4000	5333	6666	8000	9333	10,666	12,000	13,333
4	1000	1000	2000	3000	4000	5000	6000	7000	8000	9000	10,000
5	1250	800	1600	2400	3200	4000	4800	5600	6400	7200	8000
6	1500	666	1333	2000	2666	3333	4000	4666	5333	6000	6666
7	1750	572	1142	1715	2288	2858	3428	4000	4571	5142	5714
8	2000	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
9	2250	444	888	1333	1777	2222	2666	3111	3555	4000	4444
10	2500	400	800	1200	1600	2000	2400	2800	3200	3600	4000

BLOCK DIAGRAM OF A FREQUENCY DIVIDER WITH DIVISOR TABLE

FIGURE 13

binary switching code to provide division of the input frequency by any integer from 1 to 10. A special digitally coded switch (EECoSWITCH) was obtained to do this switching from the Electronic Engineering Company of California. This switch, when properly connected, made it possible to set a decimal number on the thumbwheel of the switch which in turn coded the frequency divider by applying the binary-coded voltage outputs of the switch to the programming terminals of the counter. This greatly increased the effectiveness of the final frequency-divider network, since any integer value for the source frequency could be used between 1 to 10 MHz, and 4 kHz could still be obtained by simply changing the thumbwheel setting to the integer value of the source frequency (in MHz).

The output pulses of the SM-153 were less than 30 nanoseconds in duration. This was not wide enough to trigger the next counter in the chain. For this reason, some noninverting delay was created (as recommended by Sylvania) by inserting a non-inverting buffer between the output terminal and the "set enable" terminal of the SM-153. The particular buffer that was available for this use was the Motorola MC788P. This amount of delay widened the pulse duration to approximately 100 nanoseconds which was enough to ensure reliable triggering of the next counter in the chain. The last two counters in the chain were Texas Instrument SN 5490J Decade Counters which were each used as divide-by-five dividers.

For any integer MHz frequency input, the output of this divider network could always be programmed to provide a 4-kHz frequency, as is shown in the division table of Figure 13. The advantage of this frequency-division technique, besides its adaptability to various input

frequencies, is that the final output frequency has the same frequency stability as the input signal. A schematic of the circuit, a list of the parts used to construct the frequency-divider network, and the printed circuit board layout on which the frequency divider was built are shown in Appendix (B).

The voltages required for the five counters of the frequency-divider network were +5.0 Vdc and +3.5 Vdc. These were supplied by constructing two voltage regulators from a circuit recommended by Fairchild Semiconductor Products [Ref. 18] which uses their μA723 Voltage Regulator integrated circuit. The circuit schematic for these voltage regulators and the printed circuit board layout on which they were mounted are shown in Appendix (C).

D. A TEMPERATURE-COMPENSATED CRYSTAL OSCILLATOR (TCXO) AS THE RANGING SIGNAL SOURCE

The next step was to find a suitable signal source of sufficient stability which could be used to drive the frequency divider and then frequency modulate the sonobuoy carrier. First choice, due to the power limitations mentioned earlier, was a TCXO.

The TCXO obtained was an OE-30 model manufactured by the International Crystal Co. It was a low-cost, low-powered (less than 50 mA @ +9.5 Vdc) TCXO which was advertised by the manufacturer to have a frequency stability of better than $\pm 2 \times 10^{-7}$ over the temperature range from $- 30^{o}$ to $+ 60^{o}$. The OE-30 did not provide a sinusoidal out-out. Its actual output waveform was a negative-going pulse train with a slight positive overshoot. The SM-91 input counter of the frequency-divider network required a sinusoidal signal or a positive-going signal, so it was necessary to build an inverting amplifier for the output

of the OE-30. At the same time a voltage regulator was constructed to provide the proper regulated voltage to the OE-30. The voltage regulator was another circuit recommended by Fairchild Semiconductor using their μA723 Voltage Regulator integrated circuit, but was different than the one used for the frequency-divider network. The OE-30 waveform, the voltage regulator schematic, and the inverting amplifier circuit are shown in Appendix (D).

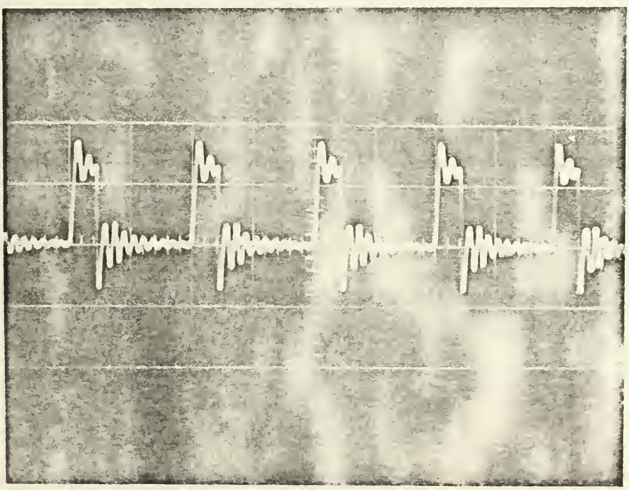
By placing this oscillator in an environment where the temperature was limited to a degree or so of variation, it was hoped that the stability could be improved enough to permit utilizing the OE-30 as the ranging signal source. This oscillator was placed in a temperature-controlled environment along with its voltage regulator and inverting amplifier to test for any improvement of frequency stability. The improvement in frequency stability of the TCXO over the manufacturer's specification was almost insignificant. The test indicated that the TCXO obtained could not be used in this manner to provide the frequency stability required for the ranging signal source.

E. AN OVENIZED CRYSTAL OSCILLATOR AS THE SOURCE

The final oscillator considered for use as the source was an ovenized crystal oscillator. It was hoped that the temperature control would provide the required stability and that a particular oscillator could be obtained which would not require too much power for its oven. A very extensive search was made of the ovenized crystal oscillators available on the commercial market with major emphasis on obtaining an oscillator with the best combination of low cost, low power consumption, quick warmup and high frequency stability. No individual oscillator

was located in the search whose specifications could fulfill all these requirements. It was finally decided to compromise somewhat on the power consumption consideration in order to continue the evaluation. The final oscillator which was purchased was the Austron, Inc., Sulzer Model 1105-2 Crystal Oscillator, Serial No. 433.

The 1105-2 is a relatively small package of 3-1/2" x 2-1/2" x 1-1/4" maximum dimension. It requires 350 mA at +5 Vdc ± 5% for powering the oven and 50 mA at +5 Vdc ± 1% to power the oscillator circuit. The particular model obtained had a 1-MHz positive-going, square-wave output for driving TTL logic. The waveform of the output is shown in Photograph 1.



PHOTOGRAPH 1. Oscillator, Model 1105-2, output signal waveform. Vertical scale: 2 volts/division. Horizontal scale: 0.5 microsecs/division.

The test data sheet provided with the oscillator indicated the following frequency stability characteristics:

Frequency change due to temperature variation

$< 2 \times 10^{-8}$ from $0^{o}C$ to $+55^{o}C$

Frequency change due to oscillator supply voltage variation

$< 5 \times 10^{-9}$ from +5 Vdc input $\pm$ 2%

Frequency change due to oven supply voltage variation

$< 5 \times 10^{-9}$ from +5 Vdc input $\pm$ 5%

Final drift rate

2×10^{-9} per 24 hours after 72 hours

Mechanical Tuning Range

$+ 98.6 \times 10^{-8}$ to -118.0×10^{-8}

Electronic Tuning Range (by varying the voltage across an internal varactar diode)

6.2×10^{-8} , 1 to 7 Vdc controlling voltage

The regulation required by the test data sheet for the oven and oscillator voltage supplies demanded that a good voltage regulator be used to obtain the best frequency stability. The voltage required for the oven and oscillator of the 1105-2 was the same as the +5.0 Vdc voltage used by some of the counters in the frequency-divider network. It was therefore possible to use the same voltage regulator; however it was necessary to replace the bypass transistor with a transistor capable of carrying the increased current load. It was also necessary to mount a heat sink on the bypass transistor.

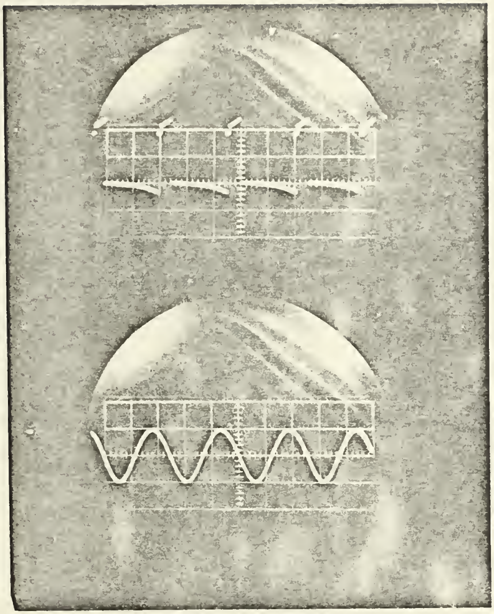
The 1105-2 oscillator was used to drive the frequency-divider network which divided the frequency down to 4 kHz from 1 MHz. It was found that the 1105-2 would not drive the SM-91 input correctly with a direct input. There appeared to be a loading mismatch. A variable resistor was placed in parallel across the input of the SM-91 between

it and the oscillator. The oscillator operated at the right frequency only when the variable resistor was adjusted to a value in the range of 100-150 ohms. Any higher or lower value caused the 1105-2 to double pulse at a frequency twice the nominal frequency. A small 47-μh coil was also added in series with the oscillator output to ensure reliable starting of the oscillator at turn-on.

The circuitry required to electronically tune the oscillator and the manner in which it was connected to the 9 pins of the oscillator's 9-pin minature header are shown on the schematic of Appendix (E). This circuitry was placed on a small printed circuit board and mounted alongside the oscillator. The printed circuit layout is also shown in Appendix (E).

F. SIGNAL INSERTION OF THE RANGING SIGNAL INTO THE SONOBUOY AUDIO FOR TRANSMISSION

Once the ranging signal had been generated it was necessary to determine the best method of inserting the signal into the band of audio frequencies that frequency modulate the sonobuoy carrier. The wave form of the ranging signal coming out of the frequency-divider network was a square wave. Frequency modulation by a square-wave signal is not advisable in general communications practices due to the bandwidths involved. Before the ranging signal could be used to frequency modulate the carrier, it had to be wave shaped into a sinusoidal waveform. This was accomplished by putting the signal through the tuned amplifier circuit shown in Appendix (B). The waveform of the signal input to the tuned amplifier from the frequency-divider network and the waveform of the output of the tuned amplifier are shown in Photograph 2.



PHOTOGRAPH 2. Waveforms of the signal input (top) and signal output (bottom) of the tuned amplifier. Vertical scale: 2 volts/division. Horizontal scale: 100 microsecs/division.

A number of locations in the sonobuoy circuitry were considered for inserting the ranging signal. It was finally decided to insert the ranging signal at the point labeled "B" on the schematic of the sonobuoy in Appendix (A). This was on the input of an emitter follower and tended to buffer the audio section from the low input impedance of the transmitter. It also seemed to be the location that caused the least distortion to the ranging signal. A first attempt to insert the signal at point "A" directly into the transmitter was unsuccessful due to the impedance mismatch.

It was discovered later in the project, when the ranging signal was transmitted to the aircraft receiver and detected, that any 4-kHz signal content in the band of audio frequencies coming through the audio amplifier would amplitude modulate the detected ranging signal. Since the amplitude of the signal had to remain constant for accurate phase comparison measurements, this intermodulation was not tolerable. For that reason it was necessary to insert a 4-kHz notch filter into the audio amplifier section of the sonobuoy to remove any 4-kHz signal content ahead of the point where the ranging signal was inserted. A 4-kHz notch filter, constructed according to the description in Appendix (B), was inserted into the audio amplifier just ahead of the emitter follower at the point labeled "B" on the sonobuoy circuit schematic shown in Appendix (A). This removed about 80% of the intermodulation effect. It was discovered that the intermodulation could be reduced even further by maintaining the signal level of the ranging signal at a much higher level than the signal level of the output of the audio amplifier. This was not difficult to accomplish, since the tuned amplifier provided a signal of large enough amplitude that it was not significantly affected by the intermodulation with the lower level of the audio amplifier output.

G. FINAL CONFIGURATION AND PACKAGING OF THE SONOBUOY RANGING SIGNAL MODIFICATION PACKAGE

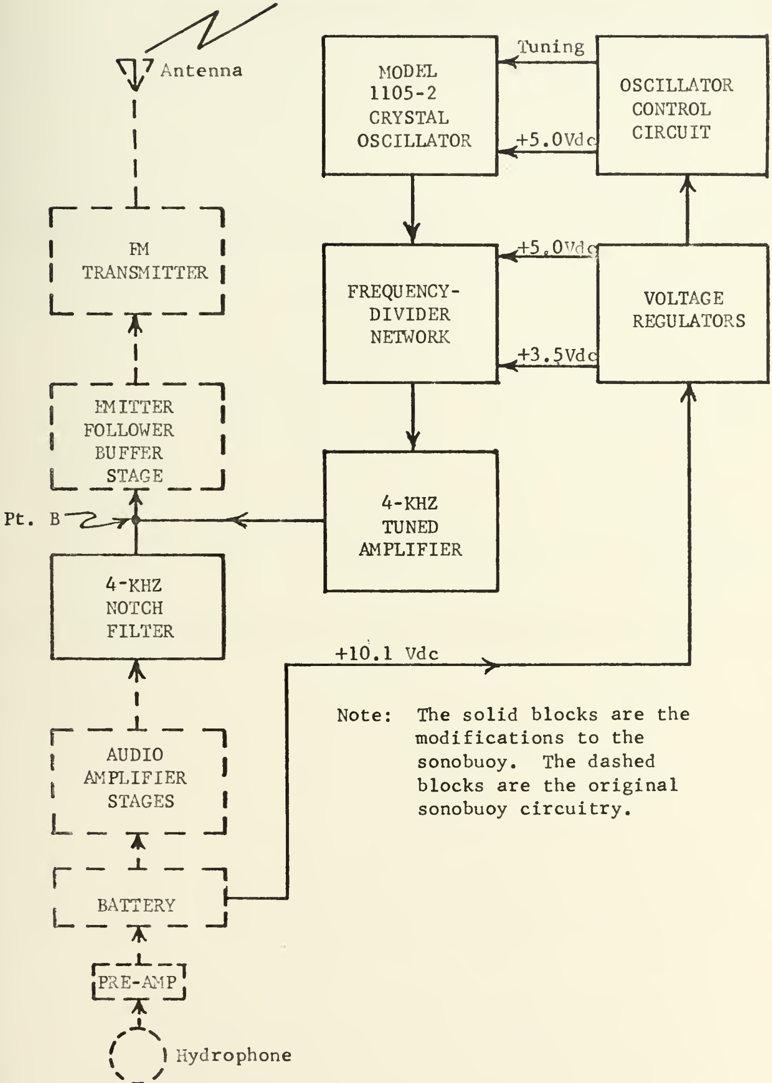
It was mentioned previously that two of the design criteria considered for this project were ease of replacing the signal source and adaptability for retrofitting the modification package into past production models of sonobuoys. With this in mind, the mounting bracket used to mount the circuit boards in another SSQ-57 sonobuoy was removed

and modified for use as the modification package mounting bracket. The major modification involved was to reshape approximately half of one side of the mounting bracket so that the higher profile of the oscillator would not interfere with the sonobuoy hull casing. A diagram of the modified mounting bracket is shown in Appendix (G).

The modified bracket was made so that the oscillator and the voltage regulator circuit board were mounted on one side and the printed circuit board containing the frequency divider network, the tuned amplifier and the 4-kHz notch filter was mounted on the other side. The small printed circuit board, with the electronic tuning circuitry and input connections for the oscillator, was mounted close alongside the oscillator in a vertical direction.

The area where the oscillator was to be mounted was designed so that the oscillator was bolted to two plates set up on spacers alongside the center channel for the cylindrical spine of the sonobuoy. In this manner the oscillator could be easily removed and replaced with another oscillator by simply removing the two bolts holding it down on the two mounting plates.

Connections from the modification package to the original sonobuoy circuitry were made by soldering connecting wires directly to the desired connection points or by cutting open a line in the circuit when it was necessary to insert a complete circuit into the internal sonobuoy circuitry (as in the case of the notch filter). The final configuration of the sonobuoy modification package is shown in block diagram form in Figure 14. The circuits for each of the blocks in the diagram are shown in the various appendices. The circuits were built on printed circuit boards whose layouts are also shown in the



BLOCK DIAGRAM OF A MODIFICATION SECTION
TO THE SSQ-57 SONOBUOY

FIGURE 14

appendices. The final packaging of the modification package is shown in the photographs of Appendix (G) where the modification package, with all the components, is shown fully installed into a SSQ-57 sonobuoy.

VI. MEASURING SYSTEM CONSIDERATIONS

The design of the aircraft section of the sonobuoy ranging system does not meet with as stringent limitations as in the case of the sonobuoy section. It is granted, however, that cost and weight of the system should be kept reasonably low just to meet cost effectiveness requirements. Fortunately, modern ASW aircraft have had margins designed into their power systems and equipment bays to handle the installation requirements of ASW systems that may come about in the future. For that reason inclusion of the proposed sonobuoy ranging system is not a major problem.

A. AIRCRAFT RECEIVING SYSTEM REQUIREMENTS

The sonobuoy ranging system as proposed would require a minimal amount of additional equipment aboard the aircraft. Since the ranging signal is standardized as the 4-kHz signal being carried on the carrier frequency of each sonobuoy's transmitter, no new receivers are needed aboard the aircraft. The 31 channel receivers currently being used could detect the ranging signal from any sonobuoy selected, since the ranging signal is part of the audio signals being transmitted on the carrier frequency of the sonobuoy. To isolate the 4-kHz ranging signal, all that is required is proper narrow-band filtering of the audio output of the aircraft receiver.

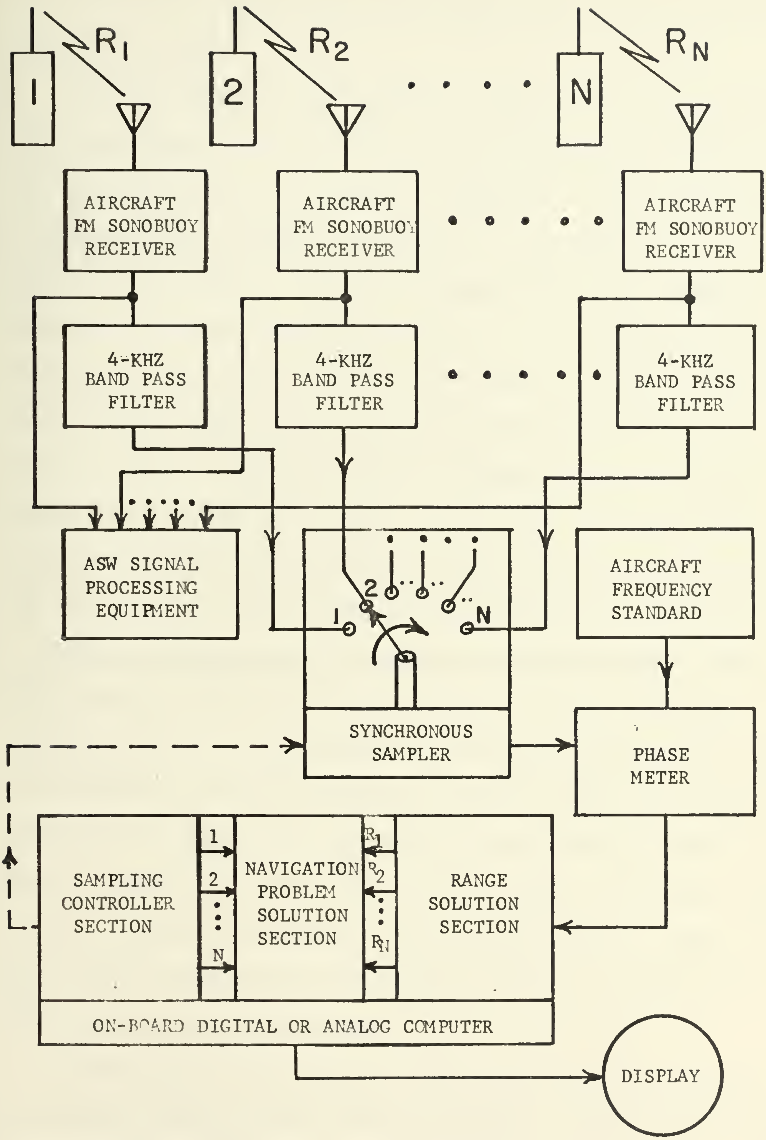
Once the ranging signal has been filtered from the audio, it must be phase compared to a reference signal of the same frequency and preferably, of higher stability. This implies a requirement for two additional pieces of equipment: a phase comparator and a tunable

frequency standard. It must be remembered, that although the discussion of this system has addressed itself to the design of a single sonobuoy package, the measuring system on the aircraft must be capable of handling ranging signals being received from a number of sonobuoys simultaneously. This could be accomplished by sampling the outputs of 4-kHz filters which would be attached to all of the aircraft receivers. Sequentially sampling the ranging signals from the various sonobuoys and using a single phase-measuring system requires the inclusion of a synchronized sampler in the final system design.

In Chapter II it was discussed how the phase difference measurement would be converted into slant range through computations by an on-board computer. But the navigation system must know to which buoy in the sampling sequence each instantaneous range value is referenced. Therefore, the computer should control the sampling sequence and the synchronization of the measuring system. The result would be a multichannel, computer-controlled synchronous measuring system as shown in Figure 15.

B. DETERMINING AN INITIAL RANGE REFERENCE MEASUREMENT

Since numerous sonobuoys are monitored, there are actually a number of ranging signals to be phase compared to the reference frequency of the aircraft frequency standard. Unless all of these ranging signal sources were tuned exactly to the aircraft reference signal before the sonobuoys were dropped, the detected signals would most likely be slightly different in frequency. This would require a separate reference frequency on the aircraft for each sonobuoy ranging signal that is received. Such a scheme would not be practical, considering



A MULTICHANNEL, SYNCHRONOUS RANGE MEASURING SYSTEM

FIGURE 15

the high cost of providing even one ultra-stable frequency standard aboard the aircraft.

Related directly to this problem of frequency differences among the ranging signal sources is the problem of obtaining an initial range reference measurement as described in Chapter II. It is recalled that a reference phase difference measurement ($\Delta\ \phi_o$) obtained at some known range must be stored for computing the range for a phase difference measurement obtained at any later instant. If this initial reference measurement could be made for all of the sonobuoy sources at approximately the same time, at zero range, and with all the sources tuned to the same reference frequency , then a reference frequency for each ranging signal would not be needed. In addition, the range computation problem would be simplified since the initial phase difference measurement ($\Delta\ \phi_o$) would be the same for all of the ranging signals being used.

There is one other major consequence of such a concept. Since all of the sources would be of the same design, they would have similar frequency stability characteristics. Hence, if they were all started at the same time, allowed to warm up in the same manner, and tuned to the aircraft reference frequency at approximately the same time, then it should be possible to account for some of the range errors that would be due to the long-term effects of the identical sources. These errors could then be eliminated by requiring the computer to subtract their effect from the range computations.

Although the concept just described solves two major problems of the measuring system, others immediately arise. Tuning of all of the ranging signal sources to the aircraft frequency standard at zero range would require activating all of the sources while they were still

aboard the aircraft. This means that an electrical interface would be required between the aircraft and each of the sonobuoys. Such an interface would have to be easily disconnected when they are dropped and would also have to be insulated against electrical shorts when the buoys go into the water. In addition, once the sources were activated while still in the aircraft, they would have to remain activated continuously from the time they were dropped until the sonobuoy finished operating. Otherwise the accuracy and convenience gained by this method of determining the initial range reference measurement would be lost. This means that power must be provided to the source in the sonobuoy while it is still aboard the aircraft during the tuning phase and also during the drop phase before it is receiving power in the water from the salt-water-activated battery.

Even with all the difficulties described above, it is felt that this concept for determining the initial range reference measurement is feasible and is still the most desirable technique for achieving the best possible range accuracy for the system. Present concepts for sonobuoy dispensers on ASW aircraft are considering sonobuoys in a prepackaged launching tube which is loaded into the launcher externally on the aircraft prior to takeoff [Ref. 19]. If a quick-disconnect, cannon plug type of connection could be designed into the sonobuoy package, the sonobuoys could be electrically interfaced with the aircraft. The electrical interface should provide the following connections:

(1) Aircraft-provided power of proper voltage and regulation to power the ranging signal source in the sonobuoy in the same manner as it is powered on battery power once it is dropped into the water.

(2) A line to electronically tune the source in the sonobuoy to the frequency of the aircraft standard.

(3) A line to sense the signal output of the source for comparing its frequency with the aircraft standard during tuning.

In the case of (1) above, the sonobuoy would also have to have a small auxilliary battery which could be activated just prior to the sonobuoy drop, and which would properly power the source until the salt-water-activated battery picked up the load after water entry. In the case of (2) above, the tuning would be most easily accomplished by using an oscillator similar to the source used in the final prototype of this project. This type of oscillator was electronically tuned by controlling the voltage across a voltage-controlled capacitive diode (VARICAP). This would require, however, that the final tuning voltage be somehow memorized and fixed upon the VARICAP in the sonobuoy before it is dropped. An exact method of doing this was not considered in this project due to the time availability, but it appeared to be within the state of the art.

It should be mentioned in the conclusion of this section that the techniques proposed by Grant for determining the initial range reference measurement were not considered to be feasible or practical. He proposed flying to an "on-top" position over each buoy for the reference measurement. But he fails to mention the problem of providing a reference signal for each sonobuoy if their sources are not at exactly the same frequency. Accurately tuning the aircraft standard to the sonobuoy's source would not be feasible during the short period of time while near the on-top position of the sonobuoy. No means is available using the on-top techniques for removing long-term stability errors as is possible in the proposed concept. Grant concluded that the interface problems of activating the sonobuoy sources prior to or during flight

would have too many design difficulties to make it feasible. This author does not completely agree, since the previously described scheme not only appears feasible, but results in many advantages, including possible corrections for some of the errors which an on-top procedure would not do. Grant implies that activation prior to flight and/or during flight would require replacement of the batteries in the un-dropped buoys after each flight. This would not be true if the source were powered by the aircraft through an electrical interface. If the sonobuoy were not launched, neither the regular salt-water-activated battery nor the small auxilliary battery required by this proposed concept would be degraded during the flight, since neither would be operated.

The discussion in this section has been restricted to conceptual proposals, since no time was available to implement any of these ideas. Such an effort could easily be a topic for extended research or another thesis on this same project area.

C. PHASE MEASUREMENT ACCURACY REQUIREMENTS

To be able to determine instantaneous range accuracy of ± 50 meters, as previously proposed, is equivalent to measuring a phase angle of $\pm$ 0.00066 wavelengths for a 4-kHz signal. To measure this kind of phase accuracy would require a phase meter capable of measuring the phase difference between two signals to the following resolution:

$$(\pm\ 0.00066 \text{ wavelengths}) \cdot (360^\circ/\text{wavelength}) = \pm\ 0.2376^\circ$$

$\therefore$ Required absolute phase measurement accuracy $\leq$ $\underline{0.2376^\circ}$

Phase meters are currently available which will measure to this degree of accuracy. Care must be taken, however, that the two signals to be

compared are of approximately the same amplitude and that the spurious harmonic content of the signals is low. Otherwise the accuracy drops considerably. This means that the ranging signal generated by the sonobuoy section of the ranging system has to be harmonically pure and amplitude stable. This was accomplished in the prototype system of this project by proper filtering in both the sonobuoy (as described previously) and in the signal recovery section of the aircraft. By insuring that no significant intermodulation took place to change the amplitude of the ranging signal, the amplitude of the signal when detected in the aircraft could be maintained constant. This was partially accomplished by the previously described notch filter in the sonobuoy and by a very narrow band-pass filter in the aircraft. One other technique that was found to reduce intermodulation problems was to filter the ranging signal from the audio signals on the output of the discriminator in the aircraft receiver instead of filtering after going through its audio amplifier. This improvement was mainly due to the fact that at the low-level output of the detector, the ranging signal had a much higher signal level than the remaining audio frequencies. Hence, harmonics of the lower frequencies that would normally be amplified by the audio amplifier and would intermodulate with the ranging signal were kept at a low level by filtering out the ranging signal before audio amplification. Their intermodulation level with the ranging signal was therefore minimized.

VII. THE RANGE MEASURING SECTION OF THE PROTOTYPE SYSTEM

Although one of the original goals of this project was to develop a complete sonobuoy ranging system prototype, the design of the aircraft measuring section of the system was limited by the availability of equipment. For that reason, major emphasis was placed on development of the sonobuoy section, and the effort toward developing the aircraft measuring system was limited to creating a workable system for evaluating the concept. Where possible, however, it was attempted to obtain equipment which could eventually be used in an aircraft installation of a prototype system when and if the project reaches that stage of evaluation. The different components and the manner in which they were put together to form a workable system are described in the following sections.

A. THE AIRCRAFT RECEIVER

At the beginning of the project it was desired to obtain one of the 31-channel ASW aircraft receivers which is actually used in current aircraft as the receiver for the system prototype. That particular receiver is the AN/ARR-52 sonobuoy receiver. Use of one of those receivers would have given a realistic evaluation of the prototype because the receiver characteristics would have been those of the actual receiver that would eventually be used in such a system. It was not possible, however, to obtain an ARR-52 due to their limited availability. As a substitute a Radio Receiving Set, AN/ARR-58, was obtained which has similar characteristics but is only a 16-channel receiver.

B. THE BANDPASS FILTER

To provide the narrow bandpass filtering at the output of the receiver, as was mentioned in the previous chapter, advantage was taken of the recent advances and improvements in hybrid integrated-circuit active filters. Active filters of this type have extremely small size, weight, and power consumption. In additon, they are very adaptable since their characteristics can easily be controlled in a tuning mode of operation using variable resistors. Their only disadvantages in the past have been a tendency for the stability of their characteristics to be overly sensitive, and slightly higher cost than passive filters. These disadvantages have been almost completely overcome by recent developments which use new negative-feedback techniques to stabilize them, and improved integrated-circuit manufacturing and packaging techniques to cut down their cost. These types of active filters are available as small (0.8" x 0.5" x 0.4") integrated building blocks. They can be used individually as medium-roll-off, lowpass, highpass, or bandpass filters by simply making the correct external connections to the terminals of the package. Using variable resistors in the form of potentiometers or field-effect transistors (FETs) as voltage-controlled resistors, the center frequency, gain, and bandwidth can be easily controlled and electrically tuned during operation. Using them as building blocks and cascading a number of them together, it is possible to construct higher-order filters of the Butterworth, Chebyshev, Cauer and Bessel types with very steep rolloffs [Ref. 20 & 21].

The active filter used as the 4-kHz bandpass filter on the output of the receiver of the prototype system was a FS-20 Hybrid Universal Active Filter manufactured by Kinetic Technology, Inc., of Santa Clara,

California. It was connected so that it had a gain of 38, a bandwidth of 174 Hz, and with the capability of tuning the center frequency over a range from 1.5 kHz to 14 kHz by varying a potentiometer. The bandpass response of the filter used in the prototype is shown in Figure 16 when the center frequency was tuned to 4 kHz. A schematic of the connections made to the filter and its configuration are shown in Appendix (F).

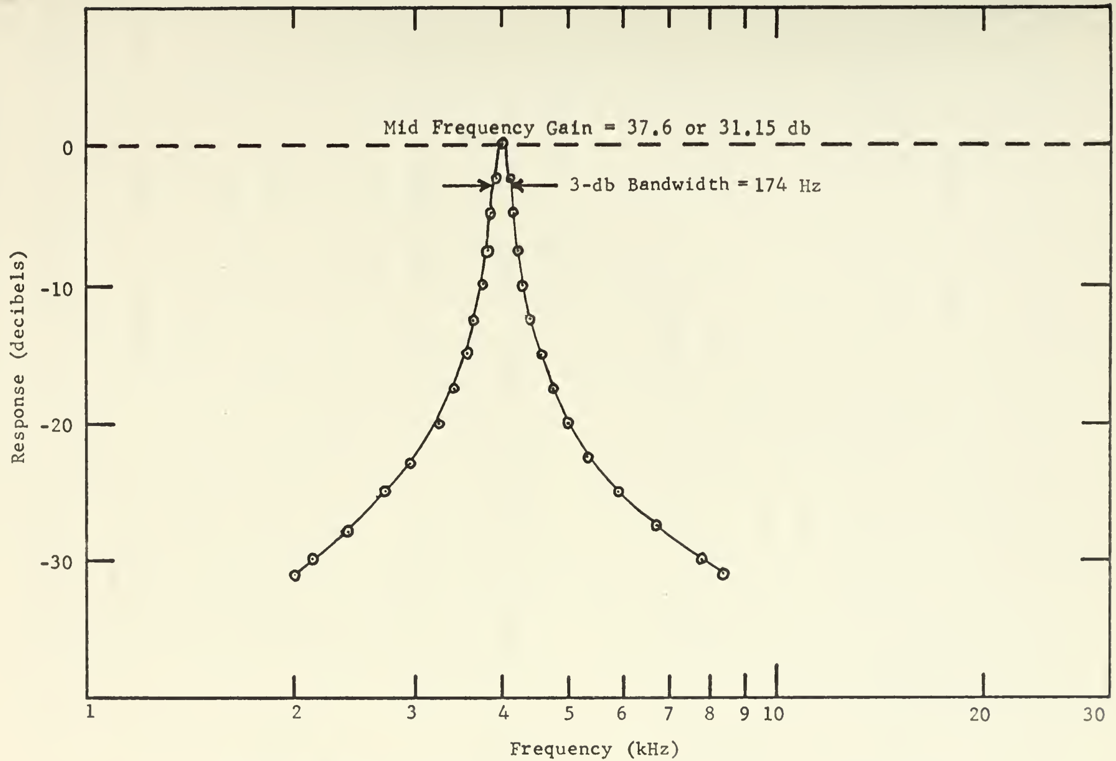
C. THE PHASE METER

The phase meter for the prototype had to be one with very good resolution and high measuring accuracy. Since the phase difference measurement would be fed to a computer of either the analog or digital type, it was preferable to obtain one with both digital and analog outputs.

The phase meter obtained for use in the system prototype was a Model 355 Digital Phase Meter manufactured by Wiltron Co. of Palo Alto, California. This phase meter had a digital readout, digital and analog outputs, an absolute measuring accuracy of ± 0.3 degrees, and many additional features which made it an ideal choice for the intended use. Among the useful additional features were adjustable filtering on the analog output to reduce phase jitter or noise on any analog recording, and also a front-mounted control for quick and easy adjustment of the zero phase-angle reference for the meter.

D. THE REFERENCE SIGNAL FREQUENCY STANDARD

The frequency standard for supplying the reference signal to the prototype measuring system should be ultra-stable and tuneable down to very small tolerances. The smaller the tuning resolution of the standard, the less critical was the tuning of the ranging signal source in the prototype.



BANDPASS RESPONSE TEST OF A FS-20 UNIVERSAL ACTIVE FILTER NETWORK

FIGURE 16

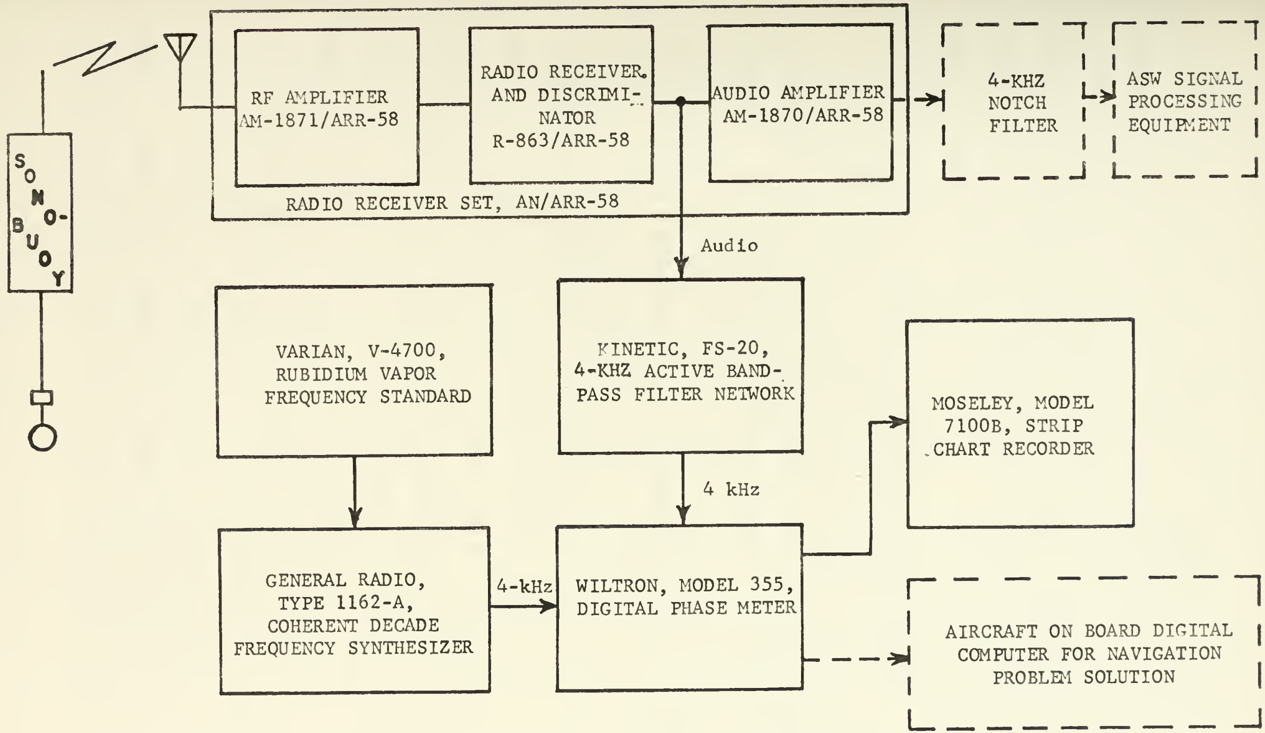
The final frequency standard for the prototype system was a General Radio, Type 1162-A Coherent Dacade Frequency Synthesizer which was phase locked to a Varian, V-4700 Rubidium Vapor, Atomic Frequency Standard, The Rubidium Standard provided a 1-MHz sine wave signal to the synthesizer which then divided it down to the desired 4-kHz output. The synthesizer was only capable of tuning resolution down to 0.1-Hz steps; however another model by the same manufacturer could be obtained for future use which has a resolution of 0.01-Hz steps. The amplitude of the synthesizer output could be varied by a front-mounted control so that it matched the amplitude of the receiver ranging signal against which it was phase compared.

E. DISPLAYING THE RESULTS

To display the measured phase difference in a meaningful manner, a Mosley, Model 7100B Strip Chart Recorder was used to record the analog output of the phase meter. With its scale calibrated by means of the scale vernier, 360 degrees or a wavelength of 75 kilometers was displayed as the full-scale (10-inch) deflection. It was possible to observe a direct analogy between the phase difference measurement and range error during laboratory test of the system. With the sonobuoy placed at a fixed range (a few meters in the laboratory), when the transmitted range signal drffted in frequency it was displayed on the recorder as a change in the phase difference measurement. The change in phase difference could be immediately scaled to an equivalent range error.

F. CONFIGURATION OF THE SYSTEM

The components as described above were assembled into a prototype measurement system as shown in Figure 17. It should be remembered when



BLOCK DIAGRAM OF THE MEASUREMENT SECTION OF THE PROTOTYPE SONOBUOY RANGING SYSTEM

FIGURE 17

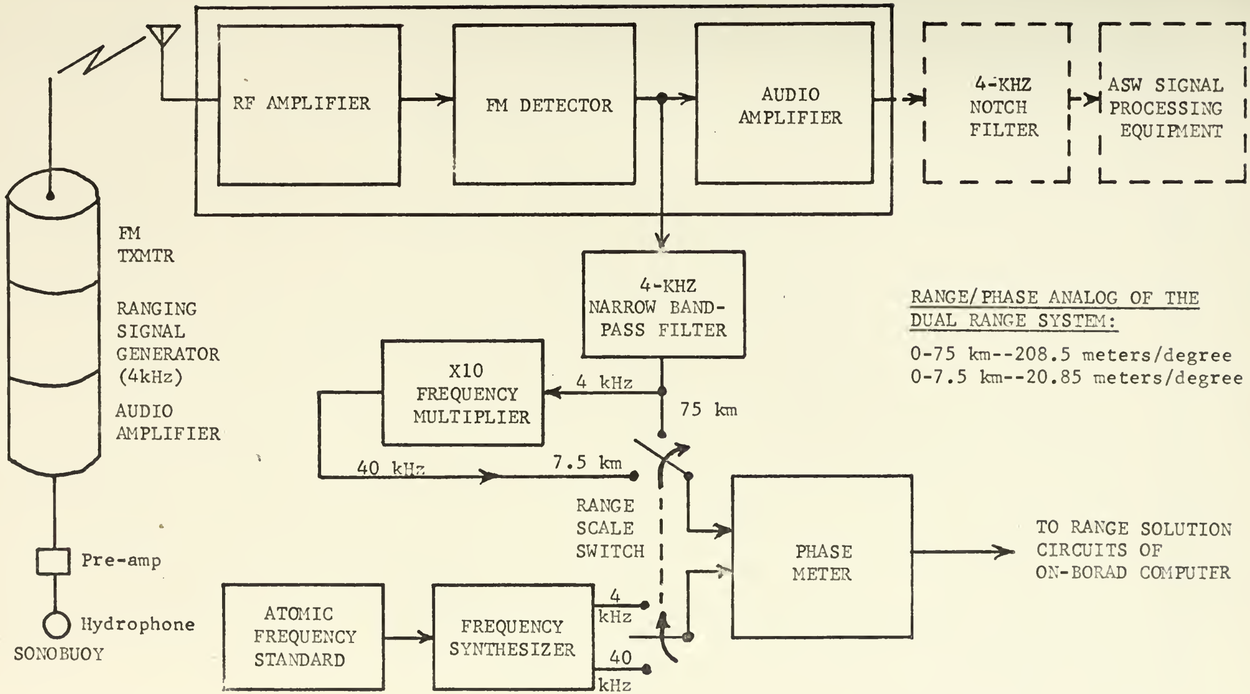
referring to this figure that this prototype is the design of a single channel of the system that would have to be developed and which was outlined in previous chapters. The sampler required in a final system design would not have any significant effect on the performance of this prototype if properly designed into the system. The blocks shown by dotted lines are system components which were not included in the prototype but would have to be included in an actual system design.

G. AN ALTERNATIVE APPROACH FOR A MEASURING SYSTEM DESIGN

The ranging signal frequency in the prototype system was selected to be 4 kHz, because of the many reasons which have been previously discussed. The degree of resolution with which a range can be measured is low at this frequency because of making the phase difference measurement near the lower limits of the resolution capability of the phase meter. Use of higher frequencies makes the wavelength shorter and makes it possible to obtain greater resolution because larger phase differences can be measured to obtain the same range measurement. However, shorter wavelengths can make it possible for a lane ambiguity to occur if the aircraft loses track of how many wavelengths it is away from the sonobuoy. In that case, the aircraft would not know how many wavelengths he was away from the sonobuoy even though he could measure the fractional distance of one wavelength that would locate his position within one of the wavelength lanes. In some navigation systems an elaborate method of counting the lanes is used to solve the lane ambiguity. Where other navigation systems are available on the aircraft, navigation information from one of these other systems could be used

with enough accuracy to resolve the lane ambiguity if a higher frequency and shorter wavelength signal were used for the ranging system.

Under present tactical considerations the percentage range accuracy that is required permits the range resolution to be much less when the aircraft is at long ranges than when it is close to the sonobuoy (and presumably closer to the nearby submarine). This implies another approach to obtain higher range resolution only at short ranges where it is most needed. The result would be a dual range scale system which uses the normal full-scale measurement of 75 kilometers at long range and, as an example, 7.5 kilometers at short range. The manner in which this could be accomplished is shown in Figure 18 and does not affect any part of the previously described ranging system except for the frequency standard and the addition of a frequency multiplier and some switching. The 4-kHz signal is still used as the incoming ranging signal in the original manner. At long ranges a range switch would be set to the 75-kilometer position. Once the aircraft had completed the detection and localization phase of the mission and had begun to manuever at closer ranges (within 7.5 kilometers) to the sonobuoys being used, then the range switch would be changed to the 7.5-kilometer position. In the 7.5-kilometer position, the incoming 4-kHz range frequency would be frequency multipled to 40 kHz and the output of the frequency synthesizer would be switched to 40 kHz. It is shown in the figure that the phase analog of the output of the phase meter is then changed from 208.5 meters per degree to 20.85 meters per degree. Thus, the resolution of the ranging system is improved ten fold making it more accurate at short ranges during the attack phase when accuracy is at a premium.



A DUAL RANGE SCALE RANGE MEASURING SYSTEM FOR HIGHER RANGE RESOLUTION AT SHORT RANGES

FIGURE 18

The original prototype system could be easily modified to incorporate the equipment needed to make it a dual range scale measuring system of this type.

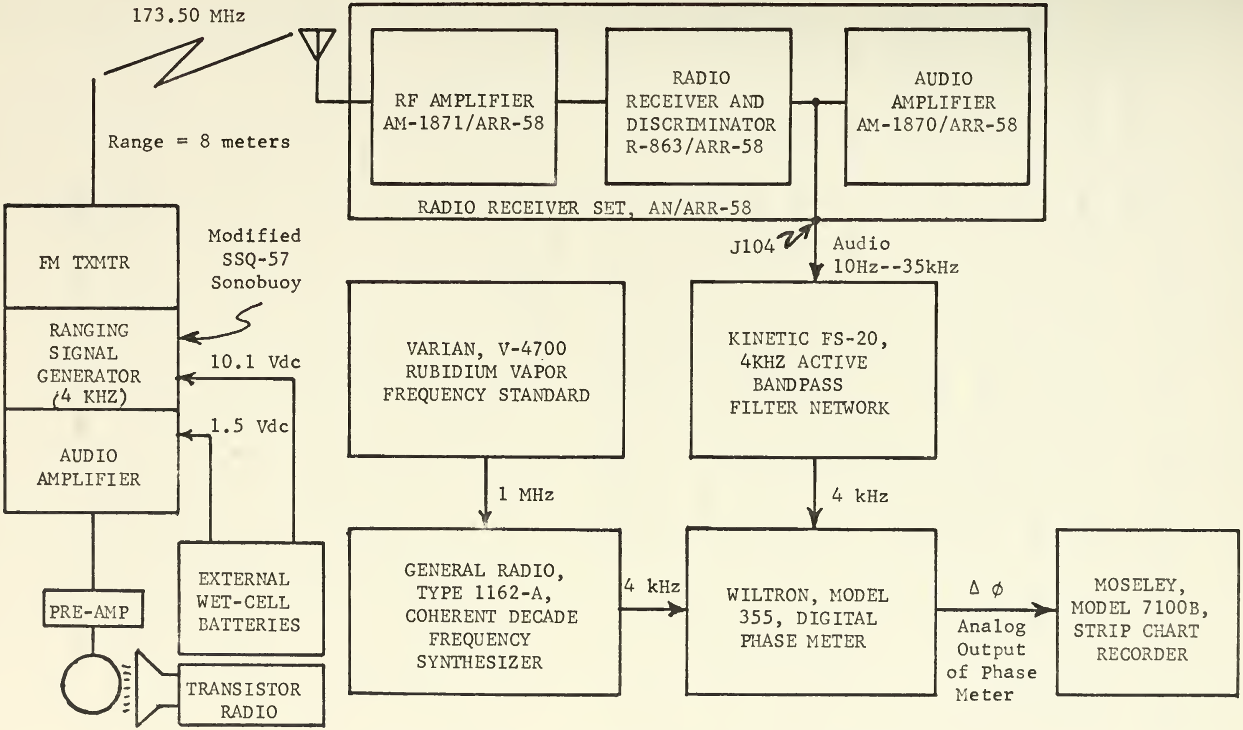
VIII. EVALUATION OF THE PROTOTYPE SYSTEM

It is recalled that the desired range accuracy for the sonobuoy ranging system was assumed to be ±50 meters. The prototype system constructed in this project was tested under laboratory conditions to determine how close it could come to providing this value of range accuracy. An actual field test of the accuracy of the prototype system was not possible due to the limited time alloted for this project. The test set up for the laboratory accuracy test is shown in Figure 19.

The SSQ-57 Sonobuoy, with the ranging signal modification package installed, was powered with external wet-cell batteries. Batteries were used instead of laboratory power supplies to more accurately simulate actual operating conditions. Use of batteries also isolated the sonobuoy from spurious line signals which had been previously observed to cause spurious phase shifts in the ranging signal generator frequency.

A small transistor radio was played into the hydrophone to create an audio band of signals. This aduio was picked up by the hydrophone and delivered to the sonic amplifier of the sonobuoy. This band of audio along with the inserted 4-kHz ranging signal were transmitted to a receiver over a fixed distance in the laboratory of about 8 meters.

An AN/ARR-58 Receiver Set was used to detect the audio signals. As mentioned previously in Chapter VI, when the output of the receiver's audio amplifier was filtered to recover the ranging signal, undesired intermodulation existed between the ranging signal and the audio signals from the hydrophone. This was overcome to some extent by filtering the audio at the output of the discriminator before the audio signals were



BLOCK DIAGRAM OF RANGING SYSTEM ACCURACY TEST

FIGURE 19

amplified by the audio amplifier. A test jack, J-104, built into the receiver test panel, proved to be a very convenient access point to the discriminator output.

The FS-20 Bandpass Filter Network, described in Appendix (F), was connected to the test jack in order to filter the 4-kHz ranging signal from the audio. The filtered ranging signal was delivered to one input of the phase meter, while a 4-kHz reference signal from the atomic frequency standard was delivered to the other input.

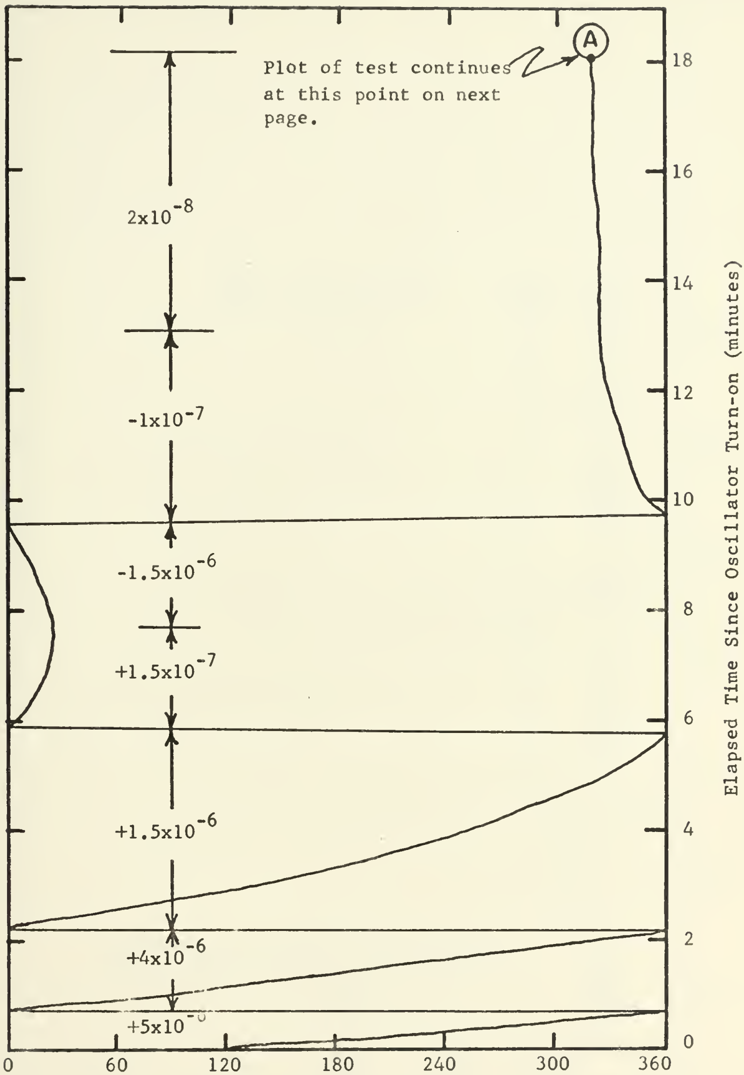
The measured phase difference between the two signals was recorded from the analog output of the phase meter on a strip chart recorder. The strip chart recorder was operated at slow speed to provide an indication of phase difference versus time. Since the two signal sources were at a fixed range from each other, any change in the phase difference measurement versus time indicated range error.

A. DISCUSSION OF TEST RESULTS

The test set up described above was first used to precisely tune the ranging signal source in the sonobuoy to the frequency of the frequency standard. This was accomplished over a period of several days during which many fine tuning adjustments were made on the Model 1105-2 oscillator which was used as the ranging signal source. Once the phase difference between the two sources was made as stable as possible over 12-hour tuning periods, it was assumed that the Model 1105-2 was tuned to the frequency of the atomic standard as closely as was permitted by the frequency stability characteristics of the Model 1105-2. The final tolerance of the tuning was measured to be within an offset in frequency of 4×10^{-10}.

After tuning the source in the manner discussed above, the sonobuoy was shut down for 26 minutes. This permitted the oscillator and the oscillator's oven to cool so that it could be restarted to determine the warmup frequency-stability characteristics of the oscillator. The time required for the oscillator to warmup and to stabilize onto the previously tuned frequency determined the amount of time delay from sonobuoy turn-on until the ranging signal could be used to accurately measure ranges.

The results of this test are plotted in Figure 20 showing the measured phase difference versus elapsed time from sonobuoy turn-on. The oscillator in the sonobuoy started slightly above the reference frequency and began decreasing in frequency as shown by the changing slope of the phase differences curves. After 7.5 minutes the phase difference measurement showed a change from negative slope to positive slope indicating that the frequency of the detected ranging signal had passed through the reference frequency and was thereafter lower in frequency. After approximately 15 minutes, the phase difference measurement changed slowly indicating that the detected ranging signal had stabilized very close to the frequency of the standard. During the period from 15 minutes after sonobuoy turn-on until 12 hours and 45 minutes later when the oscillator stopped because of battery discharge, the maximum change in the phase difference measurement was less than 45.5 degrees. For the 4-kHz reference frequency, this was equivalent to less than 31.2 microseconds of accumulated time error. From Figure 8 this converts to a range error of less than 9350 meters during the 12.75-hour period after oscillator warmup.



PLOT OF RESULTS OF RANGING SYSTEM ACCURACY TEST

FIGURE 20

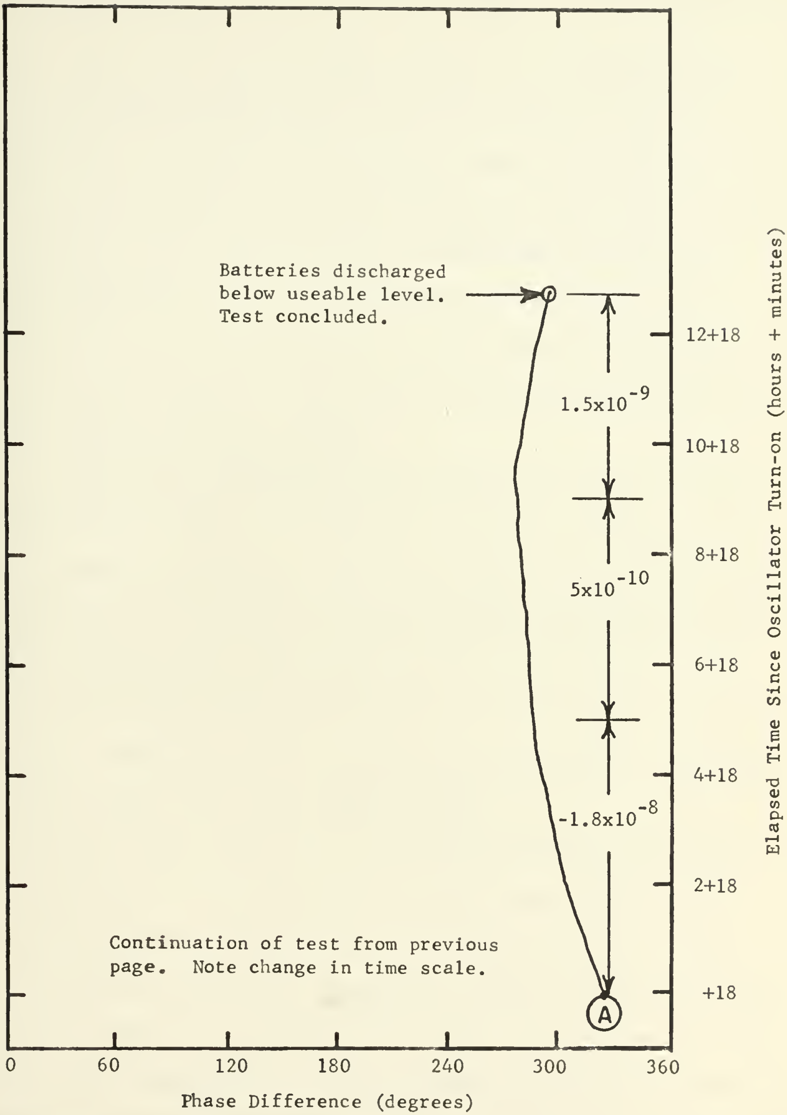
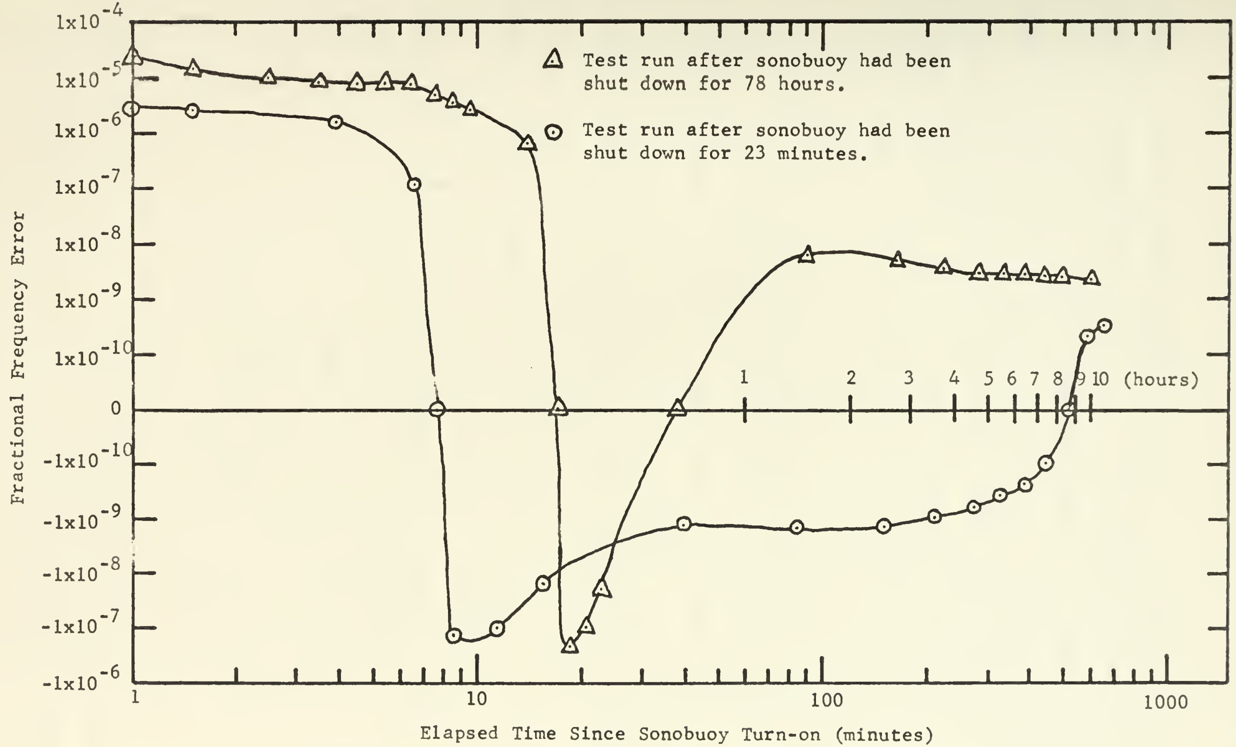


FIGURE 20 (continued)

The test indicated that the prototype system could be used to measure ranges with reasonably good accuracy if the required initial range reference measurement were delayed until after the oscillator warmup period. If the system were used for range measurements during shorter periods than the 12.75 hours of this test, the range error would be considerably less than 9350 meters. As an example, the phase difference measurement did not change by more than 2 degrees during the period from 8.3 to 9.3 hours. With an initial range measurement made at 8.3 hours, this would be equivalent to a maximum range error of 514 meters during that one hour period.

A second test was performed in the same manner as the first test to determine the effects on the warmup and long-term frequency stability characteristics by creating a longer period between shutdown and restart of the source. The second test was performed after replacing the batteries of the first test. The sonobuoy and the ranging signal source were left in an off condition for a period of 77.9 hours and were then restarted. A phase difference measurement versus time plot was recorded on the strip chart in the same manner as before.

To draw a visual comparison of the performances during the tests, the phase difference recordings of the two tests were converted to plots of fractional frequency error versus elapsed time from sonobuoy turn-on as shown in Figure 21. The manner in which this conversion was made was to measure the accumulated time error over increasing intervals of time as the ranging signal frequency stabilized onto the reference frequency. The accumulated time error for each selected time interval was converted to fractional frequency error by use of the conversion chart in Figure 9. The fractional frequency error values obtained for



PLOTTED COMPARISON OF RESULTS OF TWO RANGING SYSTEM ACCURACY TESTS

FIGURE 21

some of the time intervals in Test One are indicated on the plot of the test results in Figure 20 for reference. The center of each time interval was selected as a plotting point for the measured fractional frequency error value obtained for that interval. To expand the time scale during the warmup period when the largest deviations took place, the plotting points were plotted versus a logarithmic time scale. The resulting fractional frequency error plots obtained for the two tests in this manner were then combined to form Figure 21.

In comparing the results of the two tests plotted in Figure 21, it is noted that Test Two took approximately 10 minutes longer for the ranging signal frequency to reach the reference frequency after turn-on and approximately 50 minutes longer to warm up and stabilize to a relatively constant value. The reason for the upward shift in the fractional frequency error after about 2.5 hours during Test One could not be ascertained. The two tests indicated that when the sonobuoy ranging signal source is started from a completely "cold" start, as in Test Two, then it takes approximately 1.5 hours before it is stabilized close enough to a pretuned reference frequency to be useable for range measurements. This gave more credibility to the consideration previously discussed in Chapter VI of powering the ranging signal source by aircraft power to complete the warmup period enroute to the operating area.

The two tests showed respective offsets in the fractional frequency error of approximately 1.5×10^{-9} and 8×10^{-9} after the warmup periods. A constant fractional frequency error could be tuned out after the warmup period before dispensing the sonobuoy if it were connected in an electronic-tuning mode to the aircraft as discussed in Chapter VI. The range error could then be reduced to a minimum. If the oscillator

signal in the case of Test Two were used for range measurements by obtaining a reference range measurement sometime after the 1.5-hour warm-up period, thereby compensating for the positive offset, later range measurements made up to 10 hours after turn-on would not be in error by more than about 15 kilometers. This error was determined by noting that the fractional frequency error did not change by more than 5×10^{-9} after 1.5 hours. With the offset of $+8 \times 10^{-9}$ tuned out of the system by a reference range measurement at 1.5 hours after turn-on, the 5×10^{-9} change in the offset during the remaining 8.5 hours would accumulate approximately 50 microseconds of time error. Thus, the equivalent range error over the same period would be approximately 15 kilometers.

These tests showed conclusively that the prototype system was capable of providing reasonable range accuracy, but still not sufficiently accurate to fulfill the goal of ± 50 meter range accuracy that was previously assumed. An oscillator that is more stable than the Model 1105-2 would have to be used as the ranging signal source in the sonobuoy if greater accuracy were required. This was an expected result since the stability requirement for the source was determined in Chapter IV to be 7.38×10^{-10}/day, and the specified stability for the Model 1105-2 was only 2×10^{-9}/day.

IX. SUMMARY

After completing the design, construction and evaluation of the prototype sonobuoy ranging system developed in this project, the major conclusion reached was that the system is feasible. Present state-of-the-art limitations on the frequency stability of crystal oscillators do not permit the ranging system to achieve range accuracies as small as are desirable for ASW tactical navigation. The introduction of the system into present models of ASW aircraft and sonobuoys, however, would still provide much useful navigation information. When combined with on-board navigation systems already in use, the accuracy of the ranging system would complement and possibly improve the overall navigation accuracy of such an integrated system. A sensitivity study should be made of this type of an integrated system to see if the inclusion of the sonobuoy ranging system at its present accuracy capability would be a worthwhile addition. Factors of cost and tactical effectiveness would have to be weighed against each other before a final production model of the system could be considered.

It should be emphasized that major breakthroughs in the field of frequency control are generally considered to be close at hand due to continuing improvement in computer-aided design methods. The ranging system could be developed at present range accuracy capabilities and continuously improved by substituting oscillators of higher frequency stability as they become available. For that reason, one of the major design criteria for the prototype ranging system in this project was easy replacement of the ranging signal source in the sonobuoy without affecting the rest of the system.

The aircraft measuring section of the proposed ranging system could be easily developed using off-the-shelf measuring instruments similar to those used in this project. Studies presently being made on the best methods of using computers to solve the navigation problem from the phase difference measurements yielded by the measuring system should be continued.

The advantages of having an electrical interface between the aircraft and the sonobuoys used in the ranging system have been discussed. Further investigation of the best method to perform this interface should be made. A preliminary design study should also be considered for new dispenser system designs and sonobuoy packaging with which the ranging system would be more compatible.

Since the modification to the sonobuoy section of the ranging system increased the power requirements for the sonobuoy's battery, higher-energy batteries should be considered for future production sonobuoys. If presently available, their procurement should be arranged; if not, newer designs should be developed and contracted.

The overall cost of developing this prototype sonobuoy section of the ranging system prototype was less than $450, the major part of which was the price of manufacturing the oscillator to specifications. Since all items were purchased as single units or in small quantities, this cost could be cut down immensely by purchasing components in large quantities.

It is proposed that consideration be given to developing only certain channels of sonobuoys with the sonobuoy ranging system modification installed. It appears that the navigation accuracy would be just as

good by placing only a few of the modified sonobuoys in strategic positions when initially dropping the sonobuoy pattern. By alternating drops of modified sonobuoys and normal sonobuoys, their relative positions in the final pattern would be extremely accurate, since only a short time elapses between drops. Once the relative positions of the sonobuoys are memorized by the aircraft's computer, the aircraft could navigate relative to the pattern using ranging information from only a few of the sonobuoys in the pattern that were within range of the aircraft's receivers. The proposal for dropping modified sonobuoys on alternate drops is because the aircraft would always want to be within range of two or more modified buoys in order to determine their relative position from the aircraft. Since the pattern would be of a fixed geometric size which was accurately determined during its initial placement, the positions of all other buoys would be known relative to the measured positions of the modified buoys being received. Hence, the position of the complete pattern would be fixed relative to the aircraft with the same accuracy as the measurement accuracy of the range to any particular modified sonobuoy. Only a few of the sonobuoys that would be expended under this proposal would be higher-priced, modified models. The result would be an overall reduction in cost by a factor of at least one half.

The prototype system developed during this project was not field tested due to limited time availability. As soon as a workable solution is developed for solving the navigation problem on an aircraft computer, this ranging system should be field tested aboard an aircraft. Such a test would require a number of sonobuoys modified in the manner described in this report. A secondary goal of this project was to provide

design and construction guidelines so that numerous sonobuoy modifications sections could be constructed and installed in sonobuoys for use in such a field test. At the same time, the basic outline of a useable measuring system was given so that it could also be used for performing a field test of the overall system. Some improvement and modification of the equipment for the measuring system might be necessary, but most of the equipment used would be compatible aboard an aircraft for a field test, with the possible exception of the atomic frequency standard. The field testing of the system could in itself be the subject of another thesis study.

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APPENDIX A

SCHEMATIC OF A SSQ-57 SONOBUOY

A complete schematic of the model of SSQ-57 Sonobuoy manufactured for the Navy by Sparton Electronics is shown in Photograph 3 on the following pages. Labels have been added at various points in the schematic where circuitry has been inserted or where signals are applied from the ranging system modification package. These are referred to during the text of this report.

The notes on the drawing which were too small to be read when reproduced are restated below for reference:

1. All values are in ohms, picofarads, and microhenries unless otherwise specified.

2. M indicates millions of ohms.

3. K indicates thousands of ohms.

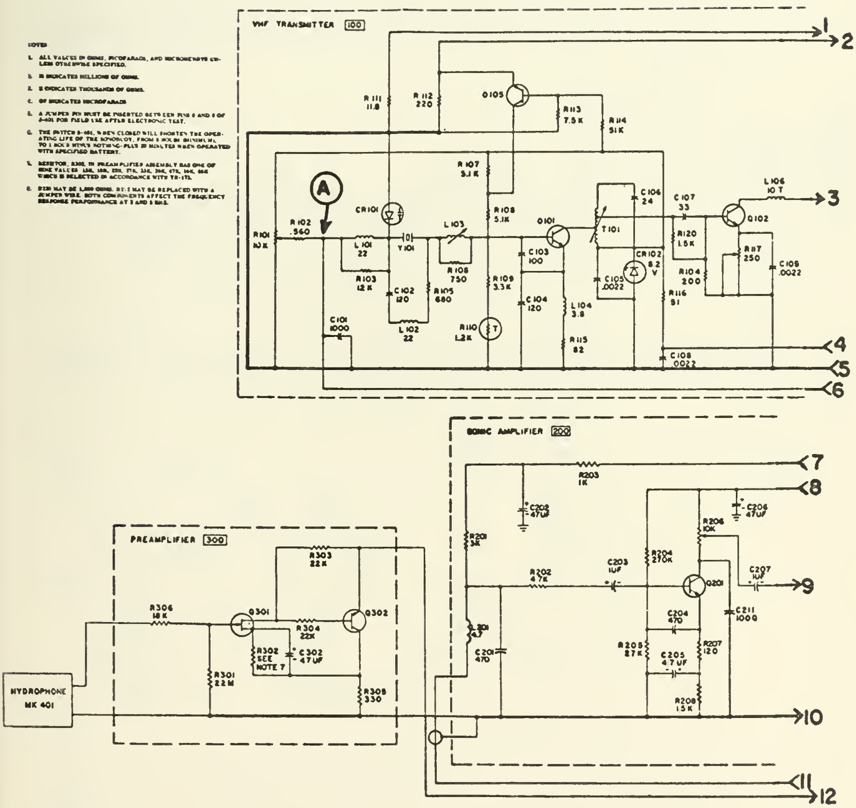
4. UF indicates microfarads.

5. A jumper pin must be inserted between pins 8 and 9 of J-401 for field use after electronic testing.

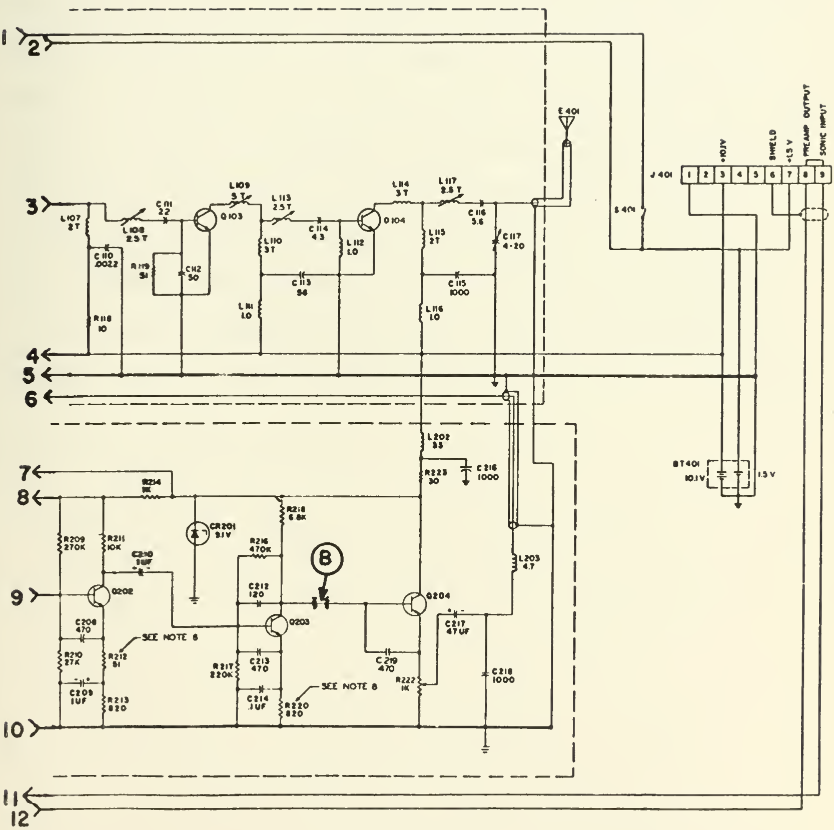
6. The switch S-401, when closed will shorten the operating life of the sonobuoy, from 8 hours (minimum), to 1 hour minus nothing--plus 20 minutes when operating with the specified battery.

7. Resistor, R302, in the preamplifier assembly has one of nine values: 15K, 18K, 27K, 39K, 47K, 56K, or 68K, which is selected in accordance with TP-173.

8. R220 may be 1,000 ohms, R212 may be replaced with a jumper wire. Both components affect the frequency response at 3 and 5 kHz.



PHOTOGRAPH 3. Schematic diagram of a SSQ-57 Sonobuoy

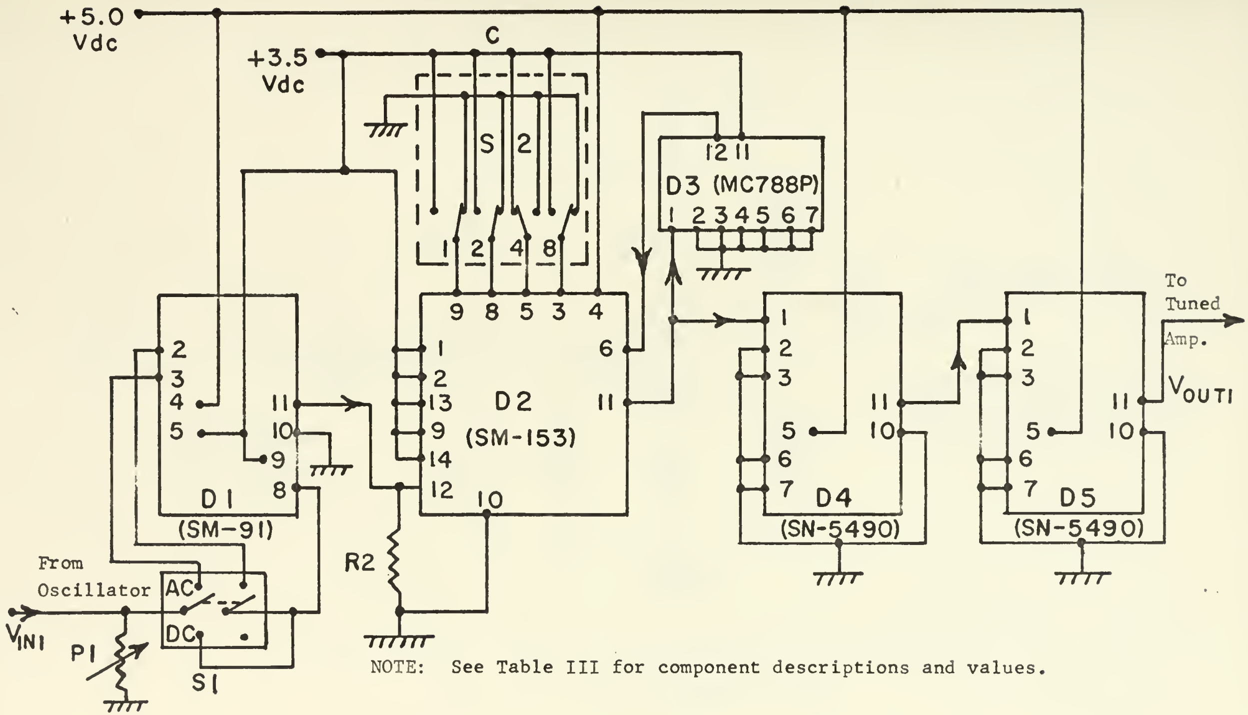


PHOTOGRAPH 3. (continued)

APPENDIX B

DESCRIPTION OF THE FREQUENCY DIVIDER, TUNED AMPLIFIER, AND NOTCH FILTER NETWORKS OF THE SONOBUOY MODIFICATION PACKAGE

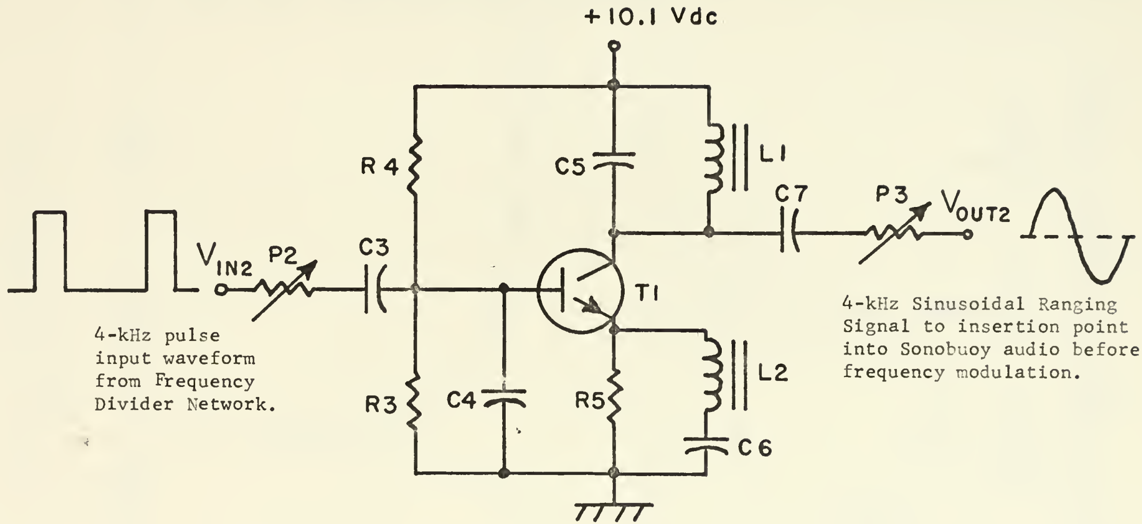
The frequency divider, tuned amplifier, and notch filter which were constructed in the sonobuoy modification section of the ranging system are described by means of circuit diagrams in the figures of this appendix. The printed circuit layout upon which these circuits were constructed is shown for reference. The configuration of components on the printed circuit layout is also shown along with a descriptive list of the components. The component numbers on the circuit diagrams indicate the identical components on the printed circuit configuration and the lists of components. The dotted lines on the configuration diagrams indicate wire connections between points on the circuit board.



NOTE: See Table III for component descriptions and values.

THE FREQUENCY DIVIDER NETWORK

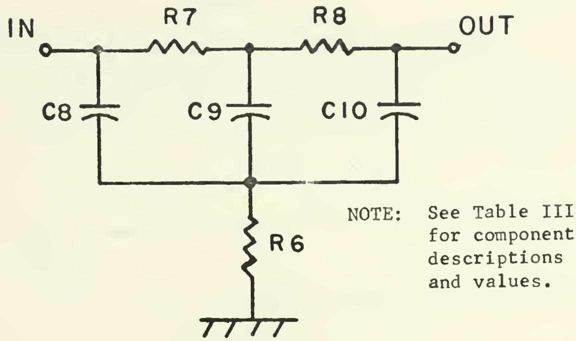
FIGURE 22



NOTE: See Table III for component descriptions and values.

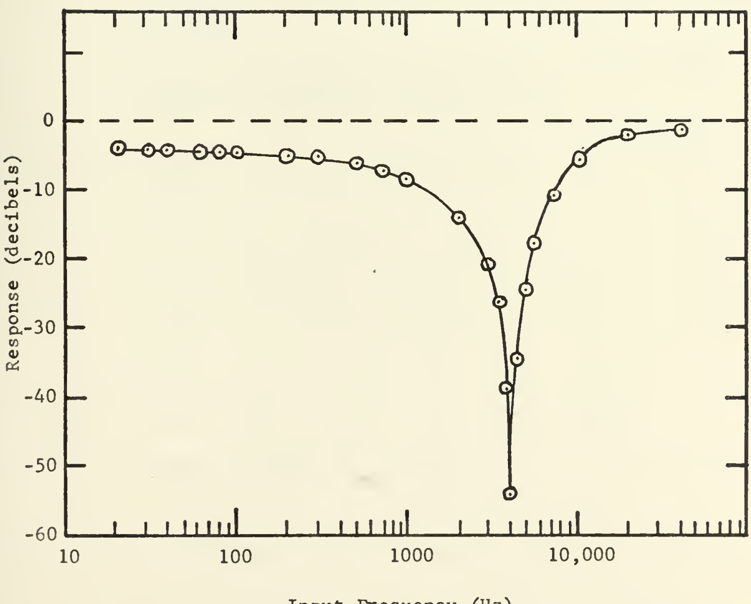
THE 4-KHZ TUNED AMPLIFIER CIRCUIT

FIGURE 23



THE 4-KHZ NOTCH FILTER CIRCUIT

FIGURE 24



RESPONSE TEST OF THE 4-KHZ NOTCH FILTER CIRCUIT

FIGURE 25

TABLE III

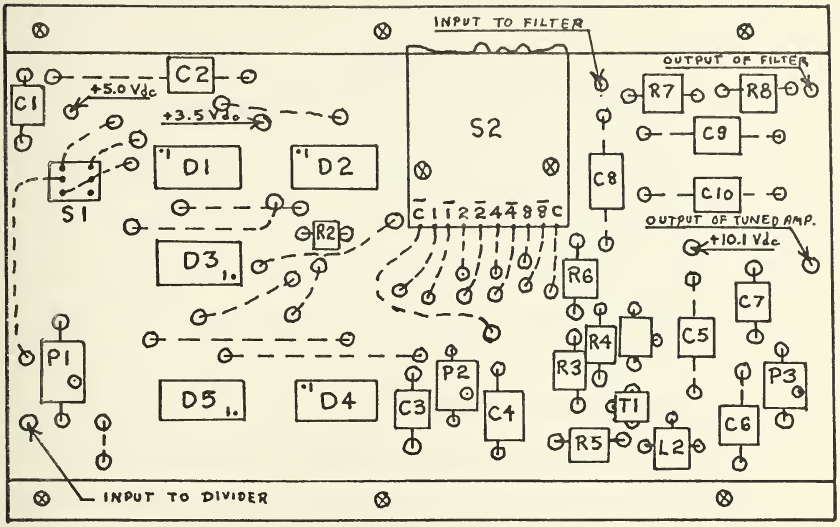
LIST OF COMPONENTS FOR THE FREQUENCY DIVIDER, TUNED AMPLIFIER, AND NOTCH FILTER

P1	1 kohm, Bourns Trimpot, Type 260P.
P2, P3	10 kohm, Bourns Trimpot, Type 3009P.
S1	DPDT Sub-minature Toggle Switch, J-B-T Instruments Co., Model 221.
S2	BCD-coded rotary thumbwheel switch, Electronic Engineering Co. of California, ECCoSWITCH Model 5257M.
D1	Decade Divider, Model SM-91, Sylvania Electronics Components Group, Semiconductor Division.
D2	Decade Programmable Frequency Divider, Model SM-153, Sylvania Electronics Components Group, Semiconductor Division.
D3	Dual 3-input Buffers, Non-inverting, Model MC 788P, Motorola Semiconductor Products, Inc.
D4, D5	Decade Counters, Model SN-5490J, Texas Instruments, Inc.
R2	68 Ω, $\pm$5%, 1/8 watt resistor.
R3	1.3 K Ω, $\pm$5%, 1/2 watt resistor.
R4	9.1 K Ω, $\pm$5%, 1/2 watt resistor.
R5	1.0 K Ω, $\pm$5%, 1/2 watt resistor.
R6	820 Ω, $\pm$5%, 1/2 watt resistor.
R7, R8	10 K Ω, $\pm$1%, precision glass type resistor.
C1	820 pf, $\pm$10%, disc capacitor
C2	200 μf, electrolytic capacitor, 15 Vdc.
C3, C7	.22 μf, $\pm$10%, mylar capacitor, 50 Vdc.
C4	.1 μf, $\pm$10%, Film wrap polycarbonate capacitor, 50 Vdc.
C5, C6	.047 μf, $\pm$10%, Film wrap polycarbonate capacitor, 50 Vdc.

(continued)

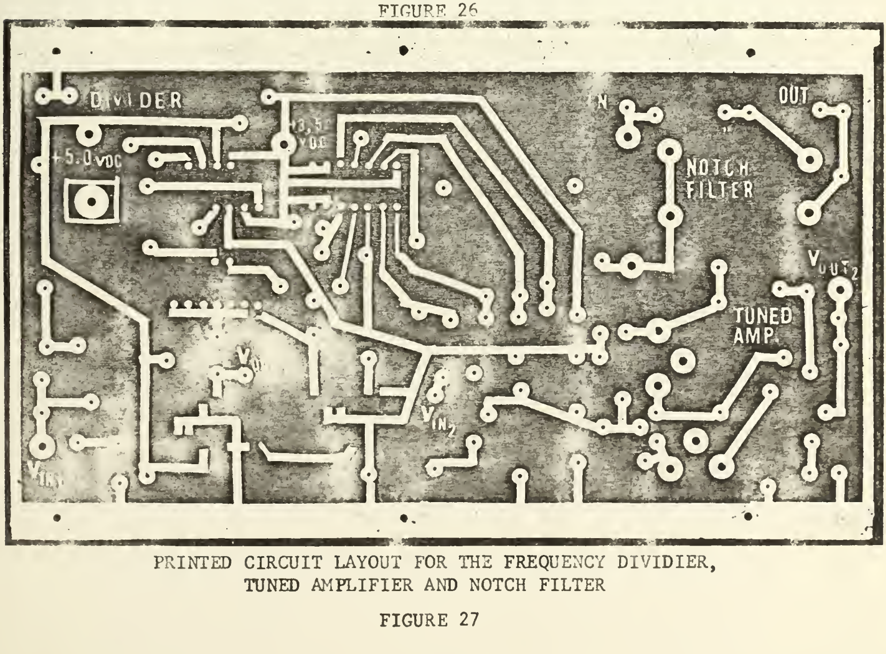
TABLE III (continued)

C8, C9, C10	6800 pf, $\pm 5\%$, silvered, molded dipped mica capacitors, 500 wvdc.
T1	2N3705, NPN Transistor, Texas Instruments, Inc.



CONFIGURATION OF COMPONENTS ON THE PRINTED CIRCUIT LAYOUT FOR THE FREQUENCY DIVIDER, TUNED AMPLIFIER AND NOTCH FILTER

FIGURE 26



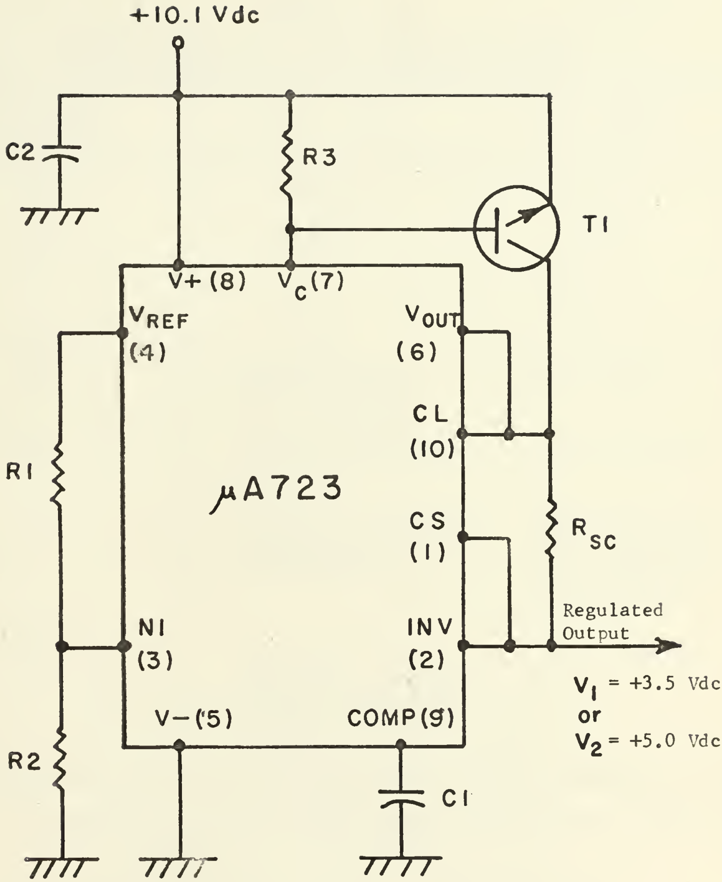
PRINTED CIRCUIT LAYOUT FOR THE FREQUENCY DIVIDIER, TUNED AMPLIFIER AND NOTCH FILTER

FIGURE 27

APPENDIX C

DESCRIPTION OF THE VOLTAGE REGULATOR NETWORKS

The voltage regulator circuits which were constructed to provide proper voltages to the oscillator and frequency divider of the sonobuoy's modification package are described by means of a circuit diagram in Figure 28. The printed circuit layout on which the regulators were constructed, a configuration diagram of the components, and a list of componenets are also shown in the appendix. Further information on the use of this voltage regulator circuit and specific data on the μA723 Integrated Circuit Voltage Regulator which is used in it, is contained in Reference 18.



NOTE: See Table IV for component descriptions and values. Numbers in parenthesis are μA723 terminal numbers.

THE VOLTAGE REGULATOR CIRCUIT

FIGURE 28

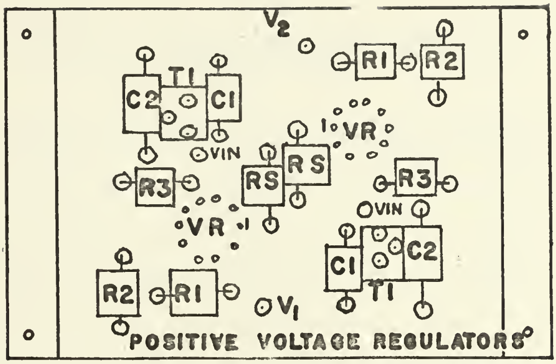
TABLE IV

LIST OF COMPONENTS FOR THE VOLTAGE REGULATORS

COMPONENT	V_1 = +3.5 Vdc	V_2 = +5.0 Vdc
R1	3.9 K Ω	2.2 K Ω
R2	3.6 K Ω	4.7 K Ω
R3	62 Ω	62 Ω
R_{SC}	2.7 Ω	0 (connecting wire)
C1	1000 pf, 5%, mylar capacitor	Same as for V_1
C2	33 μf, electrolytic capacitor, 50 Vdc.	Same as for V_1.
T1	2N5042, PNP, Silicon transistor, Fairchild Semiconductor.	2N5151, PNP, Silicon, 10 watt, Power transistor, Fairchild Semiconductor.
μA723	Precision Voltage Regulator, Fairchild Linear Integrated Circuit, Fairchild Semiconductor.	Same as for V_1.

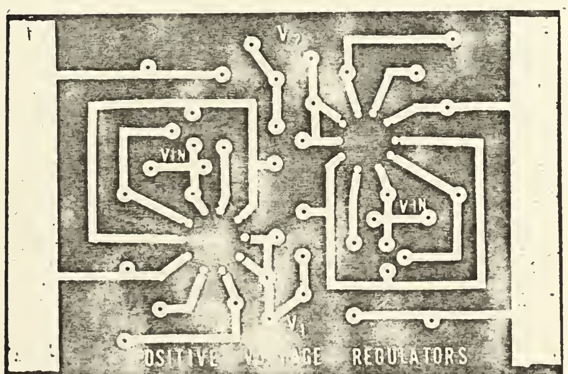
NOTES: 1) Transistors should have heat sinks mounted on them, especially T1 in the V_2 = +5.0 Vdc regulator.

2) All resistors are ±5%, 1/2 watt composition type.



CONFIGURATION OF COMPONENTS ON THE PRINTED CIRCUIT LAYOUT FOR THE VOLTAGE REGULATORS

FIGURE 29



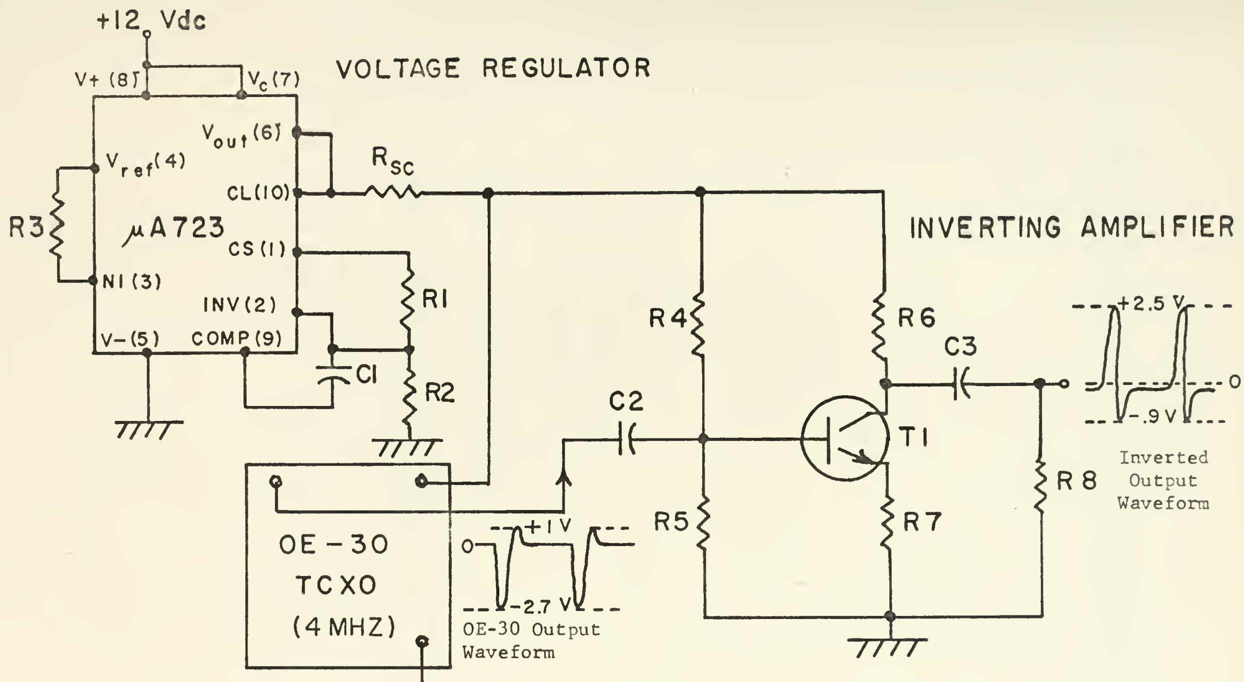
PRINTED CIRCUIT LAYOUT FOR THE VOLTAGE REGULATORS

FIGURE 30

APPENDIX D

DESCRIPTION OF THE CIRCUITRY ASSOCIATED WITH THE OE-30 TCXO

The Temperature-Compensated Oscillator, Model OE-30, made by the International Crystal Manufacturing Co., which was evaluated in this project was constructed into a breadboard circuit. Figure 31 shows the terminal connections between the OE-30 and its associated circuitry. The associated circuitry includes a voltage regulator to supply the correct voltage to the OE-30, and an inverting amplifier to reverse the polarity of the output signal of the OE-30 so it would drive the positive-logic frequency-divider network used in this project.



NOTE: See Table V for component descriptions and values.

TERMINAL CONNECTIONS FOR THE OE-30 TEMPERATURE-COMPENSATED CRYSTAL OSCILLATOR (TCXO) AND ITS ASSOCIATED CIRCUITRY

FIGURE 31

TABLE V

LIST OF COMPONENTS FOR THE OE-30 TCXO CIRCUITRY

R1	2.2 K Ω
R2	6.8 K Ω
R3	1.6 K Ω
R_{SC}	10 Ω, $\pm$5%, 1 watt
R4	1.5 K Ω
R5	470 Ω
R6	160 Ω
R7	51 Ω
R8	150 Ω
C1	100 pf ceramic
C2, C3	0.1 μf disc ceramic, 50 Vdc
T1	2N 708, NPN Transistor (h_{FE} = 80)
μA723	Precision Voltage Regulator, Fairchild Linear Integrated Circuit, Fairchild Semiconductor
OE-30	4 MHz, Temperature-Compensated Crystal Oscillator, International Crystal Manufacturing Co., Inc.

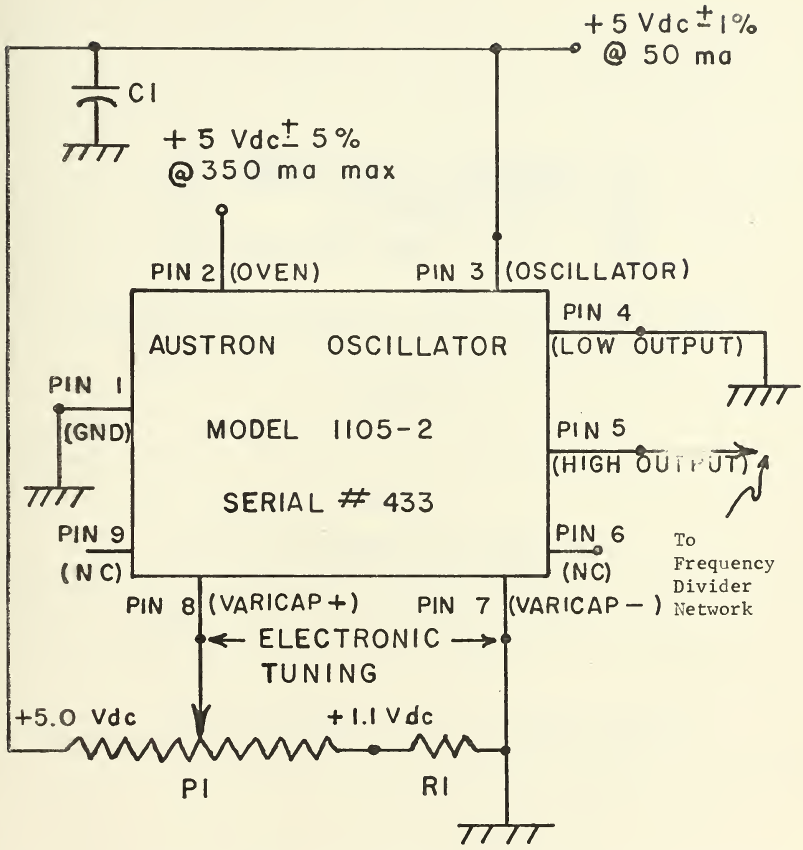
NOTE: 1) All resistors are $\pm$5%, 1/2 watt unless otherwise stated.

2) T1 should have a small heat sink mounted on it.

APPENDIX E

DESCRIPTION OF THE TERMINAL CONNECTIONS OF THE MODEL 1105-2 OSCILLATOR AND ITS ASSOCIATED CONTROL CIRCUITRY

The ovenized oscillator which was evaluated in this project was the Model 1105-2, made by Austron Inc. The terminal connections between it and its associated control circuitry are shown in Figure 32. The associated control circuitry consisted of a resistor network for electronically tuning the oscillator, and a terminal section for interconnecting the voltages from the voltage regulator to the header of the oscillator. The printed circuit layout, on which the associated control circuitry was constructed, a configuration diagram of the components and a list of the components are also shown in this appendix.



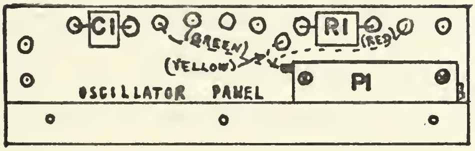
NOTES: 1) The voltage between pins 7 and 8 should never be allowed to go below 1 Vdc nor above 25 Vdc.

2) Oven and oscillator can be powered from the same +5.0 Vdc source if regulation requirements are met.

3) A small 47 μh inductor in series with the output will ensure more reliable starting of the oscillator when initially turned on.

TERMINAL CONNECTIONS FOR THE MODEL 1105-2 OSCILLATOR AND ITS ASSOCIATED CONTROL CIRCUITRY

FIGURE 32



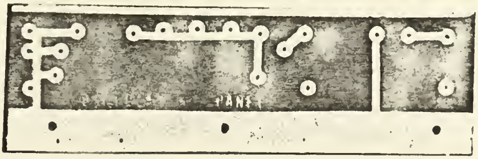
CONFIGURATION OF COMPONENTS ON THE PRINTED CIRCUIT LAYOUT
FOR THE MODEL 1105-2 OSCILLATOR CONTROL CIRCUIT

FIGURE 33

TABLE VI

LIST OF COMPONENTS FOR THE MODEL 1105-2
OSCILLATOR CONTROL CIRCUIT

C1	.025 μf, disc ceramic capacitor, 50 Vdc
R1	2.7 K Ω, 5%, 1/2 watt resistor
P1	10 K Ω, potentiometer, Bourns Trimpot, Type 236L



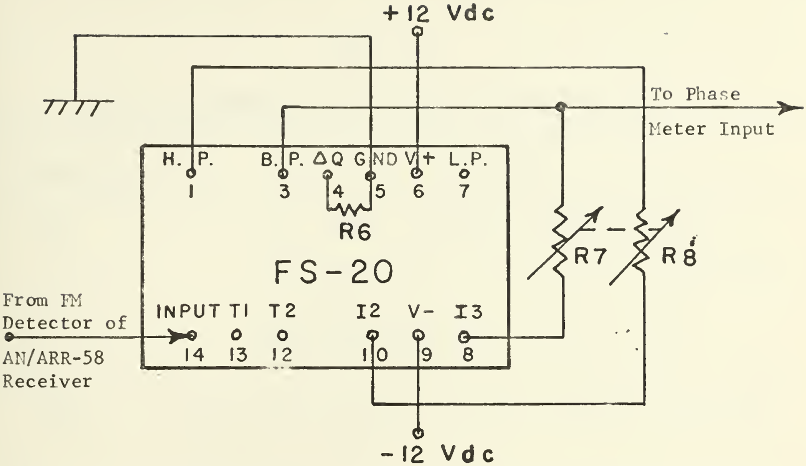
PRINTED CIRCUIT LAYOUT FOR THE MODEL 1105-2
OSCILLATOR CONTROL CIRCUIT

FIGURE 34

APPENDIX F

DESCRIPTION OF THE BANDPASS FILTER USED FOR RECOVERING THE RANGING SIGNAL IN THE AIRCRAFT MEASURING SYSTEM

The tunable bandpass filter which was constructed in this project made use of a FS-20 Universal Active Filter, made by Kinetic Technology Inc., (KTI). The terminal connections between the FS-20 and the remaining circuitry of the filter, as well as a list of components are shown in Figure 35. Photograph 4 shows the relative size and configuration of the constructed filter. Further information on the characteristics of the FS-20 and how to use it in building various types of filters is contained in Reference 21.

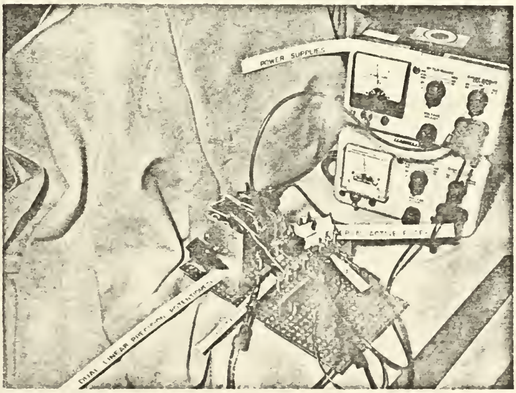


NOTE: 1) Configuration is for operation in simultaneous tuning mode with constant Q.

2) See Table VII for component descriptions and values.

4-KHZ TUNABLE BANDPASS FILTER NETWORK

FIGURE 35



PHOTOGRAPH 4. Configuration of a tunable bandpass filter using a FS-20 Universal Active Filter.

TABLE VII

LIST OF COMPONENTS FOR THE TUNABLE BANDPASS FILTER

COMPONENT	DESCRIPTION
R6	470 Ω, ±5%, 1/2 watt composition resistor
R7, R8	40 K Ω, ±1% linear precision dual potentiometer
FS-20	Hybrid Universal Active Filter, Kinetic Technology, Inc. (KTI)

NOTES: 1) These values give the following operating characteristics to the filter:

$Q = 46$ (constant with tuning)

$f_c = 4$ kHz for $R7 = R8 \approx 16$ K

Tunable range: 1.5 kHz to 14 kHz

2) More detailed information on the use of FS-20 may be found in Reference 21.

APPENDIX G

DESCRIPTION OF THE FINAL PACKAGING OF THE SIGNAL GENERATION PART OF THE PROTOTYPE SONOBUOY RANGING SYSTEM

All of the printed circuit boards described in the previous appendices were mounted on a specially modified mounting bracket which was removed from a surplus sonobuoy. The modified mounting bracket and the manner in which the oscillator and circuit boards were mounted are shown in a scaled drawing in Figure 36. Photographs 5, 6, and 7 show the configuration of the circuit boards when mounted on the modified mounting bracket. Photograph 8 shows a complete side view of the SSQ-57 sonobuoy with the modification package installed. Photograph 9 shows the other side view of the same sonobuoy.

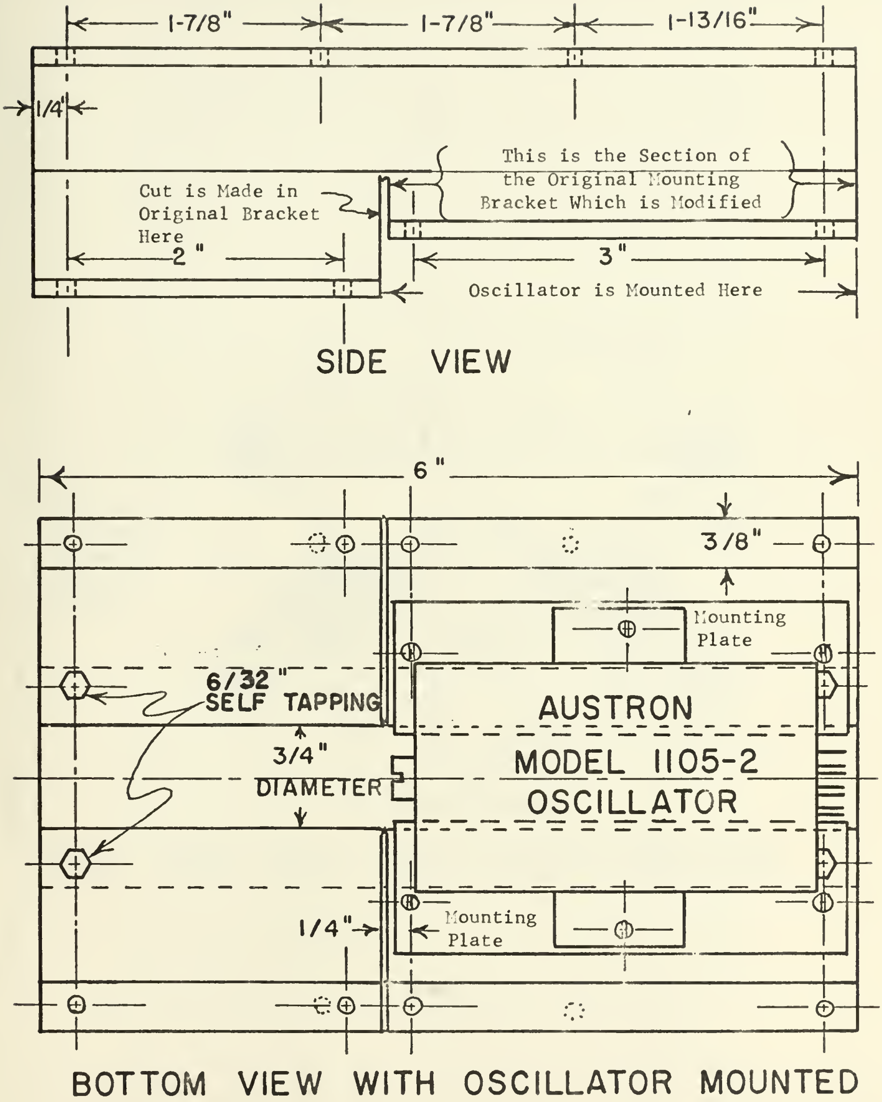
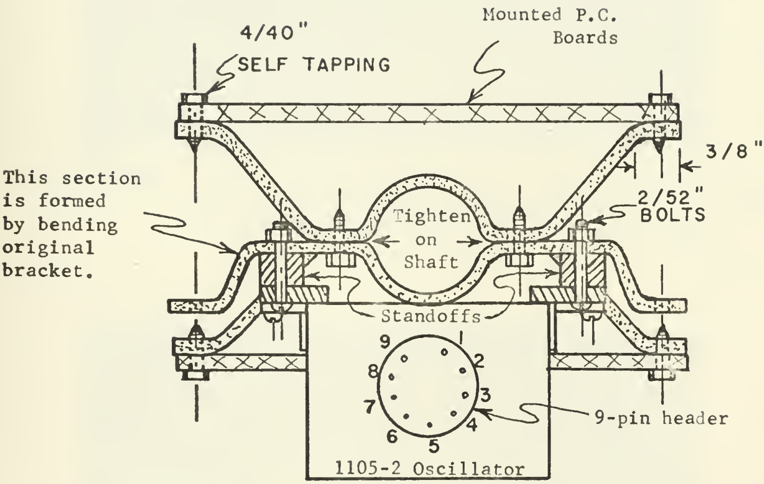


DIAGRAM OF THE MODIFIED SONOBUOY MOUNTING BRACKET

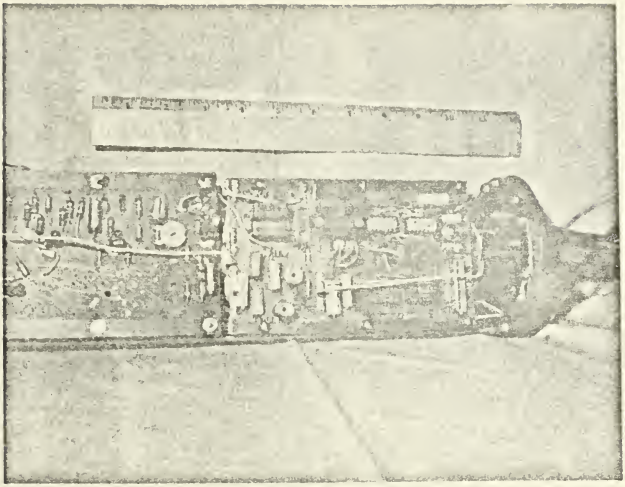
FIGURE 36



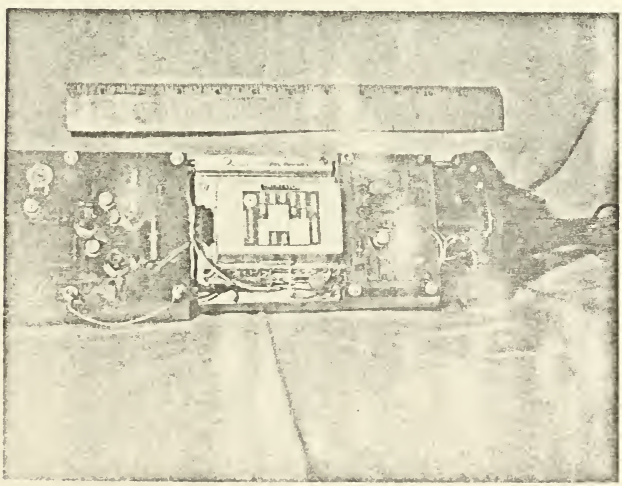
END VIEW WITH OSCILLATOR MOUNTED

NOTE: All of these drawings are made to actual scale.

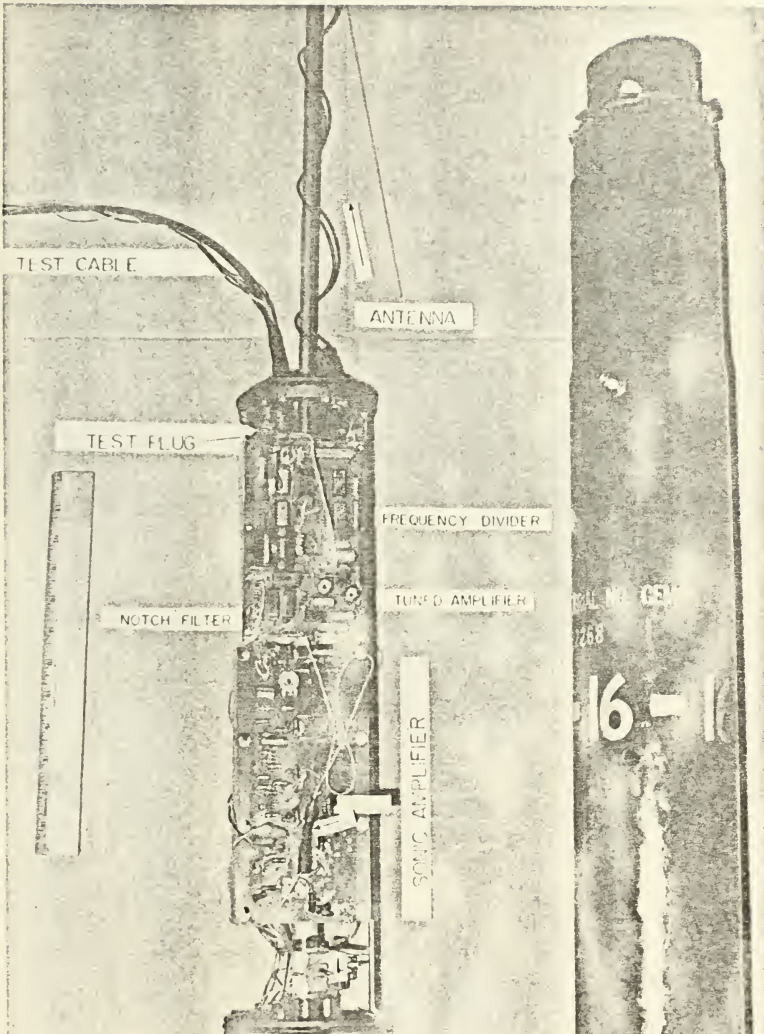
FIGURE 36 (continued)



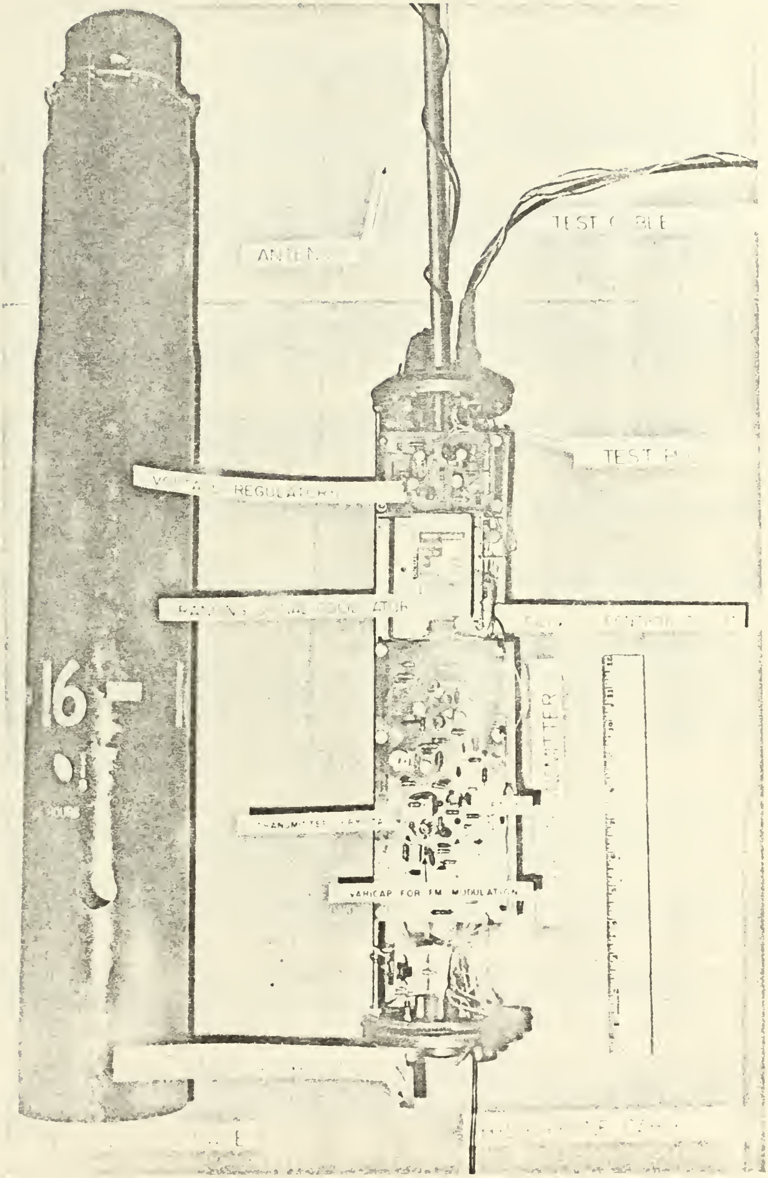
PHOTOGRAPH 5. Top view of installed modification package showing the frequency divider, tuned amplifier, and notch filter networks on the printed circuit board.



PHOTOGRAPH 6. Bottom view of installed modification package showing the oscillator and voltage regulators which are mounted on a circuit board.



PHOTOGRAPH 8. Side view of one side of a SSQ-57 Sonobuoy with the ranging system modification package installed.



PHOTOGRAPH 9. Side view of the opposite side of a SSQ-57 Sonobuoy with ranging system modification package installed.

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13. ABSTRACT

Airborne anti-submarine warfare operations require a means of precise tactical navigation relative to an air-dropped sonobuoy pattern. Advantages and disadvantages of navigational techniques which could be used to solve this problem are discussed. An analysis is made of a previously proposed method to solve this problem by sonobuoy ranging concepts. The design of a prototype sonobuoy ranging system is described, and a preliminary evaluation is made of the accuracy of the prototype system.

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